INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

Bell & Howell Information and Learning
300 North Zeeb Road, Ann Arbor, MI 48106-1346 USA
800-521-0600

UMI®

MODIFICATION AND EVALUATION OF WEPP WATER TABLE MANAGEMENT MODEL

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the Graduate
School of The Ohio State University

By

Tekin Oztekin, M.S.

*****

The Ohio State University

2000

Dissertation Committee:

Associate Professor Larry C. Brown, Advisor
Professor Andrew D. Ward
Professor Norman R. Fausey
Professor Rattan Lal

Approved by

Larry C. Brown

Advisor
Food, Agricultural, and
Biological Engineering

UMI Number: 9971613

UMI®

UMI Microform9971613

Bell & Howell Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346

ABSTRACT

Three constructed Wetland-Reservoir-SubIrrigation Systems (WRSIS) have been built in Northwest Ohio. The overall goal of this study was to model the hydrology of a WRSIS using the Water Erosion Prediction Project (WEPP) model. Modifications were made in the water balance algorithms of the WEPP hillslope model to improve the model's capability for subsurface drained cropland.

Drain flow and water table depth predictions from WEPP were evaluated against measured drain flows from North Central Ohio and water table depths predicted using DRAINMOD. Results showed that i) WEPP drain flow simulations produced large average deviations; ii) daily drain flows were overpredicted for all storm events; and iii) predicted cumulative drain flows at the end of the evaluation season for each year were almost four times larger than the measured drain flows. WEPP midspace water table depth predictions were very poor. WEPP does not predict continuous water table depths and it may not be truly simulating water table depth.

The WEPP hillslope model was modified to help improve the water balance, runoff, drain flow, and water table depth prediction capabilities for cropland where subsurface drainage, controlled drainage, and/or subirrigation systems exist or are planned. The modified model is WEPP-Water Table Management (WEPP-WTM). Most of the water balance algorithms related to subsurface drainage, controlled drainage, and subirrigation were taken from DRAINMOD. Upward flux rate from the water table was calculated using the concept of matrix flux potential.

The performance of the WEPP-WTM model in simulating runoff, drain flow, and water table depth for subsurface drained cropland conditions was tested against field measured data from two sites. Field data obtained from a North Central Ohio site were used to evaluate drain flow and runoff predictions. Water table depth predictions were evaluated against a field data set from Aurora, North Carolina. Overall, WEPP-WTM produced drain flow and runoff results similar to those from DRAINMOD and better than all of those obtained with WEPP. To evaluate the water table depth prediction accuracy of WEPP-WTM, standard errors were compared with those obtained from published results using DRAINMOD, ADAPT, and SWATREN. Overall, the predictions of water table depth from WEPP-WTM were very comparable to those from the other models.

A series of background studies were also performed to help improve the drain flow and runoff predictive capability of WEPP-WTM. These studies included: 1) evaluation of seven different saturated hydraulic conductivity estimation methods; 2) analyzing the relative impact of saturated hydraulic conductivity changes in subsurface drainage trench backfill; 3) evaluating monthly potential evapotranspiration adjustment factors; and 4) evaluating the Kirkham-Hooghoudt equations and determining the relative contribution of the Kirkham equation to drain flow predictions compared to the Hooghoudt equation alone. Furthermore, a drain flow simulation study into subsurface drainage pipes for a layered soil was conducted using the finite element based HYDRUS-2D model.

Dedicated to my mother and father

Sati and Tuncer Oztekin

ACKNOWLEDGMENTS

First, I thank my advisor, Dr. Larry Brown for providing me with the opportunity to work at the Ohio State University, and his guidance and encouragement for this research.

I thank Dr. Dennis Flanagan at the Purdue university for providing me with the WEPP fortran source code, and Dr. Norman Fausey and Eric Desmond for providing me with the field measured drain flow, runoff, and water table depth data.

I also thank Dr. Stephen Workman at the University of Kentucky, Dr. Jirka Simunek and Dr. van Genuchten at the U.S. Salinity Laboratory, and Dr. John Laflen at the USDA Soil Tilth Center Ames for providing me with information about modeling work.

I thank Dr. Andrew Ward, Dr. Rattan Lal, Dr. Norman Fausey, and Dr. John Heywood for the time that they took out of their schedule to serve on my committee, as well as the guidance that they provided throughout.

I also thank Matt Sullivan and Sandy Jones for helping me to do soil analyses.

Thanks also go to Rita Bowers, Dennis Albery, Carl Cooper, John Maul, John Pearson, Ed Poling, and William Smith for help in various aspects of my research.

I thank the following people who contributed their time and effort to the WRSIS project over the last couple years: Dr. Barry Allred, Dr. Larry Brown, Bruce Clevenger, Bernie Czartoski, Dr. Norman Fausey, Jonathan Hothem, N'Deye Marie N'Jie, Jennifer Kemerer, Leslie Zucker, Mary Shininger, Yogesh Ganesan, and Eric Zwierschke.

I am thank full for the financial support by the Gaziosmanpasa university of Turkey, the Ohio Agricultural Research and Development Center (Hatch Project H-965), Department of Food, Agricultural and Biological Engineering, the Ohio Sea Grant College Program, the North Central Regional Water Resources Research institute, the international program for water management in Agriculture, and the Overholt Drainage Education and Research Program at the Ohio state university.

Finally, none of this would have been possible without the support of my family.

VITA

February 3, 1969 .... Born - Gemerek/Sivas, Turkey

1989 .... B.S. – Agricultural Engineering Department at Ankara University

1991 .... M.S. – Agricultural Engineering Department at Uludag University

1994 .... Research Assistant in the Agricultural Engineering Department at Uludag University

1995-present .... Graduate Research Associate in the Department of Food, Agricultural, and Biological Engineering at The Ohio State University

PUBLICATIONS

1. Oztekin, T., L.C. Brown, P.M. Holdsworth, A. Kurunc and D. Rector. 1999. Evaluating drainage design parameters for wastewater irrigation applications to minimize impact on surface waters. Applied Engineering in Agriculture 15(5):449-455.

2. Oztekin, T., P.M. Holdsworth, L.C. Brown, A. Kurunc and D. Rector. 1997. Evaluating drainage design parameters for wastewater irrigation applications to minimize impact on surface waters. An ASAE Presentation Paper No. 97-2166.

3. Oztekin, T., P.M. Holdsworth, L.C. Brown, A. Kurunc and D. Rector. 1998. Evaluating drainage design parameters for wastewater irrigation applications to minimize impact on surface waters. 17-27. In Proc. of the 7'th International Drainage Symposium. ed. L.C. Brown. ASAE. 738 p.

4. Oztekin, T., N.M. N'Jie, J. Hothem, L. Luckeydoo, L.C. Brown, N.R. Fausey, B.J. Czartoski, and G. Mills. 1998. Monitoring system for water quality and quantity, and ecological parameters at the DARA wetland-reservoir subirrigation system site. An ASAE Presentation Paper No. 98-2110.

FIELDS OF STUDY

Major Field: Food, Agricultural and Biological Engineering
Soil and Water Engineering

TABLE OF CONTENTS

Page

Appendices:

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

To sustain agricultural production by protecting natural resources is an important concern of the future. Reuse of runoff water at small scales for irrigation purposes is one method for protecting the environment, which, at the same time, helps agricultural production. This concept can be considered especially for areas that have much runoff during non-growing periods and do not have enough irrigation water during the growing period to supply the water requirements of agricultural crops. After collecting runoff and subsurface drainage water in soil and water conservation structures, like a constructed wetland and a reservoir, the harvested water can be used for irrigation purposes, especially during summer months.

In Northwest Ohio in the Ohio portion of the Maumee River basin, three constructed wetlands have been designed, constructed, and linked with water supply reservoirs for corn and soybean production using subirrigation. These three constructed Wetland-Reservoir-SubIrrigation Systems (hereafter stated as WRSIS) are located at: 1) the Defiance Agricultural Research Association (DARA) in Defiance County; 2) the Shininger farm in Fulton County; and 3) the Marsh Foundation in Van Wert County. Each WRSIS project consists of four separate components: a constructed wetland, a water supply reservoir or pond, a subirrigated field and a subsurface drainage comparison area. At each site, the constructed wetland was located on prior converted cropland. All primary facilities have been built and installed at the three sites (Brown et al., 1998). As of Autumn 1999, instrumentation for water, sediment and chemical data collection at the DARA site has been completed.

At the DARA site, most of the runoff and subsurface drainage water feeding the wetland and reservoir comes from the comparison area, which cover about 70% of the total site area of 10.9 ha (27 ac). The wetlands were constructed to receive runoff and subsurface drainage water from the adjacent comparison areas, resulting in potential zero discharge from those fields directly to streams, except during extreme precipitation events. Runoff and subsurface drainage recharge the constructed wetland seasonally, and the wetland acts as a detention basin. In the wetland, some sedimentation may occur and some chemicals including nitrate and phosphorus may be trapped and/or removed. After the water has filtered through the wetland, it can be pumped into the reservoir or diverted out of the system. The reservoir serves as a supplemental water supply source for subirrigating corn and soybean crops in adjacent fields. From the reservoir, the water is pumped back through the subsurface drainage system to subirrigate crops or discharged offsite. This system is especially suitable for Ohio where water supply during summer months is a limiting factor and subirrigation has a strong potential to produce increased crop yields.

The overall purpose of the WRSIS project is to demonstrate how construction and management of wetlands coupled with subirrigation can be economically profitable for farmers, thus stimulating the adoption of wetlands and reducing adverse impacts of agricultural runoff in the Maumee River Basin (Brown et al., 1998). The specific objectives of the WRSIS project are: 1) develop one to five WRSIS sites, replacing 7% of the prior converted cropland with constructed wetland at each site; 2) construct a water balance for each site; 3) demonstrate that runoff and subsurface drainage discharges from each site will be reduced by 85%; 4) demonstrate that sediment, nitrate and phosphorus loading at each site will each be reduced by 75%; 5) demonstrate that crop yields at each site will exceed county averages by 30%; 6) survey the development and retention of wetland vegetation and wildlife habitat; 7) conduct a simple economic analysis of production inputs and outputs, and demonstrate that the WRSIS is an economically viable option for farmers; 8) develop an operation and management guide; and 9) teach 50 farmers how the WRSIS might have potential for their land (Brown et al., 1998). In addition, this system may contribute to increased and sustained levels of agricultural production, provide flood control, improve water quality by reducing off-site losses of sediment, nutrients, and pesticides, and re-establishes wildlife habitat areas.

1.1 BACKGROUND

1.1.1 Northwest Ohio

Topography in the Maumee River Basin is flat. The land use is approximately 82% cropland, 11.4% classified as other or urban land, and 6.5% as forest land. The soils are dominantly heavy clay-glacial deposits, and lake bed sediments (MVRCD, 1994).

In the early 1800's, northwest Ohio was the last area to be settled. In the 1850's, the federal drainage laws were passed and settlers began to move into the area. A series of extensive, man-made drainage outlets permitted the area to be drained, cleared, and farmed. Water management practices are critically important for continued agriculture in this area. Landowners in the region are encouraged to use technologies for surface drainage, subsurface drainage, and best management practices necessary for sustained agriculture and improved water quality (MVRCD, 1994).

Agriculture in Northwest Ohio and within the Lake Erie basin has a substantial impact on the water quality of the region. For Lake Erie, the annual sediment load from its tributaries is about 6.5 million Mg (mega gram), which is several times larger than the loading for any of the other Great Lakes (Baker, 1993). The annual total phosphorus loading for Lake Erie is about 10,000 Mg. Agricultural nonpoint sources contribute 7,000 Mg of this loading (Baker, 1993). The Lake Erie water quality is a direct result of poor cropping management practices incorporated with outdated surface and subsurface water management techniques (MVRCD, 1994). The crop management practices such as fall plowing, excess fertilizers, and not using crop rotation are direct sources of sediment, phosphorus, nitrate, and pesticides that enter Lake Erie.

1.1.2 Wetland Status in Ohio and Constructed Wetlands

In spite of their beneficial properties, more than 53% of original wetland areas in the United States were lost by the late 1980s, primarily because of human-induced land-use conversions (Mitsch and Gosselink, 1993). For Ohio, Mitsch and Gosselink (1993) estimated a net loss of more than 1.8 million hectares from the 1780s to 1980s. Wetland losses in Ohio were reported to be about 85% or more by Czartoski et al. (1995), Stuart et al. (1992), and Mitsch and Gosselink (1993). Most of Ohio's remaining wetlands are part of either the coastal wetland areas or woodlands. Although wetland losses have slowed, they still occur, and attempts are being made to protect the remaining wetlands through major state and federal provisions aimed at protecting or enhancing existing wetlands, restoring former wetlands, and/or creating new wetlands.

The International Union defines wetland as areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish, or salt including areas of marine water, the depth of which at low tide does not exceed 6 meters (Mitsch and Gosselink, 1993). A book definition of constructed wetland is " a designed and man-made complex of saturated substrates, emergent and submergent vegetation, animal life, and water that simulates natural wetlands for human use and benefits" (Hammer, 1992). Wetland creation refers to the construction of wetlands where they did not exist before (Mitsch and Gosselink, 1993). Constructed wetlands are designed to compensate for the rate of conversion of natural wetlands, to treat or improve wastewater or stormwater (municipal, industrial, or agricultural) quality, to provide flood control, and to produce food and fiber (Kadlec and Knight, 1995). Wetland restoration usually refers to the rehabilitation of wetlands that may be degraded or hydrologically altered and often involves reestablishing the vegetation (Mitsch and Gosselink, 1993). There are many constructed wetlands associated primarily with the construction and restoration of farm ponds in the Midwest (Mitsch and Gosselink, 1993).

For the purposes of the overall WRSIS project, the goal is to incorporate some type of wetland into an agricultural water management and farming system. Therefore the wetland type may be any combination of the following: created wetland, natural wetland, restored wetland, and constructed wetlands as created and/or restored. For the purposes of this thesis, the term constructed wetland will be used hereafter, as appropriate.

1.1.3 Wetlands and Effects on Hydrology and Water Quality

Many studies have shown that subsurface drainage waters may contain elevated levels of nitrate-nitrogen, sometimes in excess of the US Environmental Protection Agency (USEPA) water quality standards for nitrate-nitrogen (10 mg/L). Melvin and Kanwar (1991) described the potential role of reservoirs and wetlands in remediation of drainage waters, and suggested that a reservoir used for storage and reuse of drainage water for irrigation provided excellent renovation of drainage water by significantly lowering nitrate-nitrogen concentrations. Considerable capacity of wetlands to remove nitrate-nitrogen was confirmed by Crumpton and Baker (1993). They stated that when mesocosms[1] with residence times of approximately one week were loaded with 3 to 15 mg/L of nitrate-nitrogen, percent nitrate-nitrogen removal exceeded 80%. De Laney (1995) indicates that wetlands interrupt the organization and energy of yearly floodwaters by spreading out excess water in floodplains and detaining it in shallow impoundments. In addition, natural wetlands have been documented to improve water quality and encourage sediment retention on the landscape (Czartoski et al., 1996).

These wetlands help to control storm water and non-point source pollution (organic matter, suspended sediments, and nutrients, particularly nitrogen and phosphorus) from agricultural runoff. Abtew et al. (1995) evaluated for phosphorus level reductions from agricultural runoff/drainage in their constructed wetland research. They stated that the measured total phosphorus outflow concentrations were five times smaller than the inflow concentrations. A study in Texas was conducted by Teague et al. (1997) to research the effects of constructed

---

[1]: small experimental systems used to approximate the structure and function of at least some subset of critical processes and organisms in the ecosystem of interest (Crumpton and Baker, 1993)

wetlands with different level flow and constituent concentrations for the control of agricultural non-point source pollution. They indicated the following: 1) the average total suspended sediment reduction was 5.2%; 2) the overall reduction for nitrate-nitrogen and nitrite was 27.6 and 57.5%, respectively; and 3) the overall reduction for phosphorus was 27.7%.

1.2 WATER TABLE MANAGEMENT SYSTEMS AND CROP YIELDS

Water table management is the management or control of water conditions within the soil profile of agricultural lands (Brown et al., 1997). Water table management practices include subsurface drainage, controlled drainage, and subirrigation. There are at least two water table management practices in a WRSIS.

1.2.1 Subsurface Drainage

Subsurface drainage is the removal of excess soil water in time to prevent damage to crops because of a high groundwater table (Ritzema, 1994). In subsurface drained fields, drain tubes are installed underground with a downward slope and excess ground water is removed by these tubes by gravity.

Subsurface drainage is used to lower the water table and to create an aerated region within the plant root zone. Subsurface drainage improves trafficability, enhances field conditions for planting and harvesting, and helps decrease crop damage resulting from saturated soil and standing water (Brown et al., 1997). Schwab et al. (1975) report a ten-year average increase of 100% in corn yields from subsurface drainage with conventional tillage in northern Ohio. In Michigan, after drainage system installation, farmers estimated average yield increases of 49, 50, 59, 62, 66, and 77% for oats, corn, wheat, sugarbeets, alfalfa, and field beans, respectively (Robertson et al., 1979).

1.2.2 Controlled Drainage

Controlled drainage can be defined as any drainage system which allows gravity or pumped drainage only after the water level in the drainage ditch, pump sump or water table in the field has risen to a level where drainage should be provided to prevent crop damage (Broughton and Madramootoo, 1991; Evans and Skaggs, 1996). This water table management practice helps keep water available for plant use longer than does subsurface drainage. It can also be used to recharge the water table between growing seasons. In addition, controlled drainage may provide reductions in nitrate losses from subsurface drained croplands, and helps to increase crop yields (Brown et al., 1997; Evans et al., 1995). Under controlled drainage, a potential yield increase may depend on several factors. For example, Tan et al. (1998) summarized their research results in Ontario, Canada, indicating that the controlled drainage system had very little effect on soybean yields in 1995 and 1996 because of extremely dry soil conditions during the growing season. However, Tan et al. reported that the use of controlled drainage helped reduce the number of dry days during the growing period.

1.2.3 Subirrigation

In a subirrigation system, one system is used for supplying both drainage and irrigation water to crops. Irrigation water is supplied through the subsurface drainage system using control structures to regulate the water table levels. When using subirrigation, water is added to the soil profile through the subsurface drainage pipes. Water is pumped into the drainage outlet to maintain the outlet water level at a set point, or weir elevation.

For some soils, subirrigation is very efficient and most crops respond well to subirrigation. Significant crop yield improvements have been observed when appropriate subirrigation systems were implemented. Fausey and Cooper (1991) summarized their research results at Wooster, Ohio, stating that, with a subirrigation/drainage system, soybean yields averaged 5.22 Mg/ha compared to 3.44 Mg/ha with subsurface drainage alone. In addition, Fausey (1994) states that yield increases of 22% for corn and 45% for beans were seen in Ohio with subirrigation. Similar results for corn were seen in Michigan. LeCureux (1991) summarized his research results reporting that an average yield increase of 30% was seen with subirrigation. Although yield increases from subirrigation provide economic benefits, the net economic benefit of the system depends on a number of factors, including the cost of supplying irrigation water, managing irrigation systems, installing drainage tubing and control structures, and miscellaneous costs. After a three-year crop rotation of corn, sugar beet, and navy beans on a subirrigated field in Michigan, LeCureux (1991) stated that subirrigation generated a $118.46 per hectare advantage to the non-irrigated drainage system after paying production and pumping costs and considering amortization costs for the water control structures. In addition, Evans et al. (1996) conducted an economic analysis to compare controlled drainage, subirrigation, and drainage in North Carolina. For the conditions they described, subirrigation provided the most consistent year-to-year profit. Installing a subirrigation system may require less capital investment than installing subsurface drainage and surface irrigation systems together (Evans et al., 1996).

1.3 WATER TABLE MANAGEMENT SYSTEMS, HYDROLOGY AND WATER QUALITY

Fausey et al. (1995) state that drainage has both positive and negative impacts on water quality; i.e., a reduction in sediment and phosphorus, and an increase in nitrate-nitrogen delivery to receiving waters. Evans et al. (1995) state that runoff contains greater concentrations of sediment and organic nitrogen and phosphorus compared to subsurface drainage water, but subsurface drainage fluxes may contain very little sediment, but contains high concentrations of nitrate-nitrogen. Belcher and Fehr (1990) state that water table control systems give farmers the opportunity to control the water table for increased yield and water quality benefits. At the same time, they state that if these systems are operated improperly, they can reduce yields, increase runoff and erosion, and transport increased nutrient and pesticide concentrations and loadings.

A study conducted by Istok and Kling (1983) in western Oregon found that watershed runoff and sediment yield decreased by approximately 65 and 55%, respectively, after installing subsurface drainage. In a subsurface drainage-runoff-erosion experiment in Louisiana, Bengston et al. (1984) reported that runoff and soil erosion were reduced 29 and 16%, respectively, by subsurface drainage compared to surface drainage. Furthermore, Konyha et al. (1992) simulated the hydrology of two North Carolina muck soils using four water-management methods: conventional subsurface drainage, improved subsurface drainage, and two types of controlled drainage. They stated that improved subsurface drainage reduced runoff by 66% but increased outflow by 10%. In this study, controlled drainage moderated the effects of improved subsurface drainage. Surface and subsurface drainage usually increase total annual outflow from fields compared to natural conditions (Skaggs et., 1994). In North Carolina, studies using simulation models have shown that subsurface drainage improvements will increase total outflow slightly (on the order of 10% or less) (Skaggs et al., 1994) compared to surface drainage.

Controlled drainage may reduce total outflow by approximately 30% compared to conventional subsurface drainage (Skaggs et al., 1994), but this reduction depends on soil type, rainfall, type of drainage system, and management. Evans et al. (1995) reported that controlled drainage reduced phosphorus transport in runoff by about 40%, but had little effect on phosphorus transport in subsurface flow. They also stated that nitrate-nitrogen concentrations were 10 to 20% smaller in outflow from controlled drainage systems compared to uncontrolled drainage systems. Tan et al. (1998) stated that controlled drainage reduced nitrate loss in subsurface drainage water by 14% on a conventional tillage site and 25.5% on a no-tillage site compared to the conventional subsurface drainage system. In addition, the higher water tables with controlled drainage created an increase in runoff from the fields.

The effects of subirrigation on drainage water quality have not been researched sufficiently at this time. However, it appears that subirrigation may help reduce the losses of some potential pollutants while enhancing the losses of others. Belcher and Protasiewicz (1991) in their subirrigation research in Michigan evaluated the water quality impact of subirrigation for low and high water table levels. They stated that: 1) a water table near the soil surface reduced the nitrate-nitrogen discharge by subsurface drain flow; 2) phosphorus concentrations from high water table levels are greater than those from low water table levels; 3) subsurface drainage flow volume from the high water table levels was, on average, 22% less than the flow volume from the low water table levels

A 1995 volume of the Journal of Irrigation and Drainage Engineering of ASCE was devoted to water quality effects of water table management systems. In this volume, more research results about this issue were summarized for several regions of the U.S. by Backlund et al. (1995), Bengston et al. (1995), Fausey et al. (1995), Ritter et al. (1995), Shirmohammadi et al. (1995), and Thomas et al. (1995).

1.4 WRSIS EVALUATION AND OBJECTIVES OF THIS RESEARCH

The WRSIS sites were originally designed to detain approximately 50% of all runoff and 100% of subsurface drain flow coming from the comparison plots (Chester and Riethman, 1997). However, the detainment capacity may change from year to year because of changes in weather, crop pattern, water table management strategies, etc. There has been no research completed on the impact of a WRSIS to provide flood control, reduce erosion, improve water quality, control nutrient cycles, and detain sediment, runoff and subsurface drainage water. In addition, there is no one computer simulation model to simulate these functions of the WRSIS systems at the watershed scale.

The Water Erosion Prediction Project (WEPP) hillslope and watershed models (Flanagan and Nearing, 1995) were of interest to the author and his goal to model the efficiency of runoff, subsurface drainage water, and sediment detainment capacity of the WRSIS. However, some model modifications, especially in the water balance algorithms of the WEPP hillslope model were needed. While the current version of the WEPP hillslope model (Flanagan and Nearing, 1995) is considered a robust erosion prediction model, it contains little more than a basic subsurface drainage component. In addition, the WEPP model does not have the capability to adequately model the hydrology of agricultural lands that have controlled drainage and subirrigation systems on them, and subsequently the impact of controlled drainage and subirrigation on soil loss.

The overall purpose of this research is to modify the WEPP hillslope model, so that when it is linked with the WEPP watershed model, the linked model can be used to route runoff, subsurface drainage and subirrigation waters and sediment through the components of a WRSIS. The modified WEPP hillslope model produced through this research is called WEPP-Water Table Management (WEPP-WTM) model. The WEPP-WTM model can also be used to estimate water table depths, runoff, subsurface drain flows and soil erosion from areas having any combination of subsurface drainage, controlled drainage, and subirrigation, with impoundments, like water supply reservoirs and constructed wetlands.

Following Chapter one are seven additional chapters. Below, each chapter's purpose and specific objective(s) are summarized.

Chapter 2 describes a series of background studies thought to be interesting and necessary to improve the predictive capability of WEPP for subsurface drainage, controlled drainage, and subirrigated cropland conditions. The overall purpose of this chapter is to conduct the necessary background work to prepare input, output, and field data to be used to evaluate WEPP-WTM model. Of particular interest are model improvements for croplands where subsurface drainage, controlled drainage, and subirrigation are used. The specific objectives of the work presented in Chapter 2 are:

1) evaluate drain flow and runoff predictions using a range of saturated hydraulic conductivity test data with DRAINMOD (Skaggs, 1978);
2) analyze the relative impact of changes in drainage trench backfill properties on drainage flows and runoff;
3) evaluate monthly Potential EvapoTranspiration (PET) adjustment factors used in DRAINMOD for the prediction of drain flow and runoff; and
4) evaluate the effects of Kirkham-Hooghoudt equations on drain flow and runoff prediction accuracy of DRAINMOD against an empirical equation and determine the relative contribution of the Kirkham equation to drain flow predictions compared to the Hooghoudt equation.

Since DRAINMOD is the most popular model used in USA, the work will be conducted within the frame work of DRAINMOD.

Chapter 3 describes a study using HYDRUS-2D (Simunek et al., 1996) to model drainage flow for a layered soil with and without backfill effects. The specific objective is to develop a drain flow prediction equation, similar to that developed by Salem and Skaggs (1998), but for layered soils and backfill effects.

Chapter 4 describes an evaluation of the runoff, drain flow, and water table depth algorithms in WEPP. The specific objectives are:

1) determine the accuracy of the runoff and drain flow algorithms of WEPP using observed data; and
2) evaluate the predictions of water table depth algorithms of WEPP against those of DRAINMOD.

Chapter 5 describes the modification algorithms of WEPP hillslope model and to present the procedures used in this modification.

In Chapter 6, the modified model was tested and evaluated using two observed field data sets.

In Chapter 7, the WEPP-WTM model was linked with the WEPP watershed model, and this linked model was used to evaluate the DARA WRSIS site for predicting runoff coming to the constructed wetland for a seven month period in 1999.

In Chapter 8, the conclusions and recommendations are presented.

The work presented in several of the chapters is supplemented by additional materials that can be found in the Appendices.

1.5 REFERENCES

Abtew, W., M.J. Chimney, T. Kosier, M. Guardo, S. Newman and J. Obeysekera. 1995. The everglades nutrient removal project: A constructed wetland designed to treat agricultural runoff /drainage. 45-55, In Proc. Versatility of Wetlands in the Agricultural Landscape. ed. K.L. Campbell. AWRA and ASAE. 756 p.

Backlund, V.L., E.A. Ross, P.H. Willey, T.L. Spofford and D.M. Renner. 1995. Effect of agricultural drainage on water quality in humid portion of Pacific Northwest. J. Irrigation and Drainage Engineering, ASCE 121(4):289-291.

Baker, D.B. 1993. The Lake Erie agroecosystem program: water quality assessments. Agriculture, Ecosystems and Environment. 46(1993):197-215.

Belcher, H.W. and B.W. Fehr. 1990. Performance of a subirrigation automation system. ASAE Paper No. 902607. St. Joseph, Mich.: ASAE. 6 p.

Belcher, H.W. and L.J. Protasiewicz. 1991. Water quality impact of subirrigating maize. 281-298. In Subirrigation and Controlled Drainage. eds. H.W. Belcher and F.M. D'Itri. Ann Arbor, Michigan, Lewis Publishers. 482 p.

Bengston, R.L., C.E. Carter, J.L. Fouss, L.M. Southwick and G.H. Willis. 1995. Agricultural drainage and water quality in Mississippi Delta. J. Irrigation and Drainage Engineering, ASCE 121(4):292-295.

Bengston, R.L., C.E. Carter, H.F. Morris and J.G. Kowalczuk. 1984. Reducing water pollution with subsurface drainage. Transactions of the ASAE 27(1):80-83.

Broughton, S.R. and C.A. Madramootoo. 1991. Effects of four water table depths on soybean yields. 97-110. In Subirrigation and Controlled Drainage. eds. H.W. Belcher and F.M. D'Itri. Ann Arbor, Michigan, Lewis Publishers. 482 p.

Brown, L.C., B.J. Czartoski, N.R. Fausey and H.W. Belcher. 1998. Constructed wetland and subirrigation linkage provides high yield potential and environmentally sound corn and soybean production systems. 524-530. In Proc. of the 7'th International Drainage Symposium. ed. L.C. Brown. ASAE. 738 p.

Brown, L.C., A. Ward and N.R. Fausey. 1997. Agricultural water table management systems. Extension Fact Sheet AEX 321-97. The Ohio State University Extension, Columbus. 8 p.

Chester, P.W. and D. Riethman. 1997. Runoff storage requirements for a closed-loop subirrigation system. ASAE Paper No. 972132. St. Joseph, Mich.: ASAE. 8 p.

Crumpton, W.G. and J.L. Baker. 1993. Integrating wetlands into agricultural drainage systems: Predictions of nitrate loading and loss in wetlands receiving agricultural subsurface drainage. 118-126. In Proc. Integrated Resource Management and Landscape Modification for Environmental Protection. ed. J. Kent Mitchell. Chicago, Illinois. ASAE. 387 p.

Czartoski, J., L.C. Brown, N.R. Fausey, A.M. Brate, H.W. Belcher and R.L. Cooper. 1995. Marketing wetland for profit. 367-372. In Proc. Versatility of Wetlands in the Agricultural Landscape. ed. K.L. Campbell. AWRA and ASAE. 756 p.

De Laney, T.A. 1995. Benefits to downstream flood attenuation and water quality as a result of constructed wetlands in agricultural landscapes. J. Soil and Water Conservation 50(6):620-626.

Evans, R.O. and R.W. Skaggs. 1996. Operating controlled drainage and subirrigation systems. Publication Number: AG 356, North Carolina Cooperative Extension Service. North Carolina State University. 7 p.

Evans, R.O., R.W. Skaggs and R.E. Sneed. 1996. Economics of controlled drainage and subirrigation systems. Publication Number. AG 397, North Carolina Cooperative Extension Service. North Carolina State University. 23 p.

Evans, R.O., R.W. Skaggs and J. W. Gilliam. 1995. Controlled versus conventional drainage effects on water quality. J. Irrigation and Drainage Engineering, ASCE 121(4):271-276.

Fausey, N.R., L.C. Brown, H.W. Belcher and R.S. Kanwar. 1995. Drainage and water quality in Great Lakes and Cornbelt States. J. Irrigation and Drainage Engineering, ASCE 121(4):283-288.

Fausey, N.R. and R.L. Cooper. 1991. Subirrigation response of soybeans grown with high yield potential management. 225-230. In Subirrigation and Controlled Drainage. eds. H.W. Belcher and F.M. D'Itri. Ann Arbor, Michigan, Lewis Publishers. 482 p.

Fausey, N.R. 1994. Subirrigation/drainage systems for water table management in the Midwest. 242-246. In Proc. 15'th International Irrigation Exposition and Technical Conference, Atlanta, Georgia. The Irrigation Association. 280 p.

Flanagan, D.C. and M.A. Nearing (Eds.). 1995. WEPP technical documentation. NSERL Report No. 10, USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, Indiana. 284 p.

Hammer, D.A. 1992. Creating Freshwater Wetlands, Lewis Publishers, Inc., Chelsea, Michigan. 298 p.

Istok, J.D. and G.F. Kling. 1983. Effect of subsurface drainage on runoff and sediment yield from an agricultural watershed in Western Oregon, U.S.A. J. Hydrology 65(1983):279-291.

Kadlec, R.H. and R.L. Knight (Eds). 1995. Treatment Wetlands. New York, Lewis Publishers. 893 p.

Konyha, K.D, R.W. Skaggs and J.W. Gilliam. 1992. Effects of drainage and water-management practices on hydrology. J.Irrigation and Drainage Engineering, ASCE 118(5):807-819.

LeCureux, J.P. 1991. Profitability of a crop rotation utilizing subirrigation. 193-205. In Subirrigation and Controlled Drainage. eds. H.W. Belcher and F.M. D'Itri. Ann Arbor, Michigan, Lewis Publishers. 482 p.

Melvin, S.W. and R.S. Kanwar. 1991. Environmental and economic impacts of a recycling subirrigation drainage system. 315-326. In Subirrigation and Controlled Drainage. eds. H.W. Belcher and F.M. D'Itri. Ann Arbor, Michigan, Lewis Publishers. 482 p.

Mitsch, W.J. and J.G. Gosselink. 1993. Wetlands. New York, Van Nostrand Reinhold. 722 p.

Maumee Valley Resource Conservation and Development (MVRCD). 1994. Area Marketing Wetlands for Profit Work Plan, USDA-NRCS, MVRCD Area Office. 06825 St. Rt. 66 N, Suite C. Defiance Ohio 43512. 19 p.

Ritter, W.F., R.P. Rudra, P.H. Milburn and S. Prasher. 1995. Drainage and water quality in Northern United States and Eastern Canada. J. Irrigation and Drainage Engineering, ASCE 121(4):296-301.

Ritzema, H.P. (Ed.). 1994. Drainage Principles and Applications. ILRI Publication 16. Wageningen, Netherlands. 1125 p.

Robertson, L.S., E.H. Kidder, A.E. Erickson and D.L. Mokma. 1979. Tile drainage for improved crop production. Extension Bulletin E-909. Cooperative Extension Service, Michigan State University, East Lansing, Michigan. 11 p.

Salem, H.E. and R.W. Skaggs. 1998. Predicting drainage rates under varying water table conditions. 168-175. In Proc. of the 7'th International Drainage Symposium. ed. L.C. Brown. ASAE. 738 p.

Schwab, G.O., N.R. Fausey and C.R. Weaver. 1975. Tile and surface drainage of clay soils. Research Bulletin 1081. Ohio Agricultural Research and Development Center, Wooster, Ohio. 37 p.

Shirmohammadi, A., R.D. Wenberg, W.F. Ritter and F.S. Wright. 1995. Effect of agricultural drainage on water quality in Mid-Atlantic States. J. Irrigation and Drainage Engineering, ASCE 121(4):302-307.

Simunek, J., M. Sejna and M. Th. van Genuchten. 1996. Ground water modeling software HYDRUS-2D. Simulating water flow and solute transport in two-dimensional variably saturated media. IGWMC-TPS 53. Ver. 1.0 U.S. Salinity Laboratory, USDA/ARS, Riverside, California. 167 p.

Skaggs, R.W. 1978. A water management model for shallow water table soils. Report No. 134. Raleigh, NC. Water Resources Research Institute, Univ. of North Carolina. 175 p.

Skaggs, R.W., M.A. Breve and J.W. Gilliam. 1994. Hydrologic and water quality impacts of agricultural drainage. Critical Reviews in Environmental Science and Technology, CRC Press, Inc. 24(1):1-32.

Stuart D.G., L.C. Brown, D.L. Risley and D.L. Conrad. 1992. Ohio's wetland inventory. ASAE Paper No. 92-2120. St. Joseph, Mich.: ASAE. 10 p.

Tan, C.S., C.F. Drury, M. Soultani, H.Y.F. Ng, I.J. van Wesebeeck, J.D. Gaynor and T.W. Welacky. 1998. Controlled drainage and Subirrigation effects on crop yields and water quality. 676-683. In Proc. of the 7'th International Drainage Symposium. ed. L.C. Brown. ASAE. 738 p.

Thomas, D.L., C.D. Perry, R.O. Evans, F.T. Izuno, K.C. Stone and J.W. Gilliam. 1995. Agricultural drainage effects on water quality in Southeastern U.S. J. Irrigation and Drainage Engineering, ASCE 121(4):277-282.

Teague, L.L., A.L.Kenimer, B.J. Lesikar and F.L. Mitchell. 1997. Constructed wetlands for the control of agricultural nonpoint source pollution. ASAE Paper No. 972037. St. Joseph, Mich.: ASAE. 7 p.

CHAPTER 2

DRAINAGE MODELING STUDIES LEADING TO IMPROVED RUNOFF AND DRAIN FLOW PREDICTION CAPABILITY

2.1 INTRODUCTION

As more innovative and comprehensive agricultural water management systems and practices are developed and implemented, there is a need to improve our capability to model and assess these systems and practices. For example, agricultural water management systems are being developed and implemented in Northwest Ohio that capture, treat, and store agricultural runoff and subsurface drainage discharges for reuse as irrigation water supply. These systems are called constructed Wetland-Reservoir Subirrigation Systems (WRSIS). In modeling the effects of these systems on water quantity and quality, improved model capability is needed to properly consider all the elements in the system's water balance.

In systems containing subsurface drainage and other water table management components, determining the impact of drainage water on water quality is based not only on modeling the constituents of the drainage water, but also the volume of the drainage water. For this reason, the analysis of drainage rates and runoff with the relationships of water table depth under any combination of subsurface drainage, controlled drainage and/or subirrigation is important for designing and managing innovative water table management systems, such as the WRSIS. Many approximate models, such as the Water Erosion Prediction Project (WEPP) (Lane and Nearing, 1989) model, may have potential for this kind of analysis.

WEPP was developed by the USDA Agricultural Research Service (ARS) to estimate sediment yield and runoff by interrill and rill erosion, and erosion by concentrated flow in field-sized areas (Flanagan and Livingston, 1995). This model also predicts sediment deposition from concentrated flow into channels and impoundments. While the current version of the WEPP hillslope model (Flanagan and Nearing, 1995) is considered a robust erosion prediction model, it contains only a basic subsurface drainage component. The WEPP model does not have the capability to adequately model the hydrology of agricultural lands that have controlled drainage and subirrigation. In addition, there is no research that has appropriately evaluated the current water table depth and drain flow prediction capabilities of WEPP. The work presented in Chapter 4 addresses this need.

To predict drain flow, the current version of WEPP uses the Hooghoudt equation (Hooghoudt, 1940) as reported by Savabi et al. (1995):

$$Q = \frac{K_e(8d_eH + 4H^2)}{L^2} \qquad 2.1$$

where: Q is the drain flow depth (cm/day); K_e is the equivalent saturated hydraulic conductivity (cm/day); H is the midspace water table elevation (cm) above drain; d_e is the equivalent depth from the drain to the impermeable layer (cm); and L is the drain spacing (cm). In addition to the Hooghoudt equation, water table management models such as DRAINMOD (Skaggs, 1978) and ADAPT (Chung et al., 1992) also use the Kirkham equation (Kirkham, 1957) when the water table is close to the soil surface. The form of the Kirkham equation used in DRAINMOD is (Skaggs, 1980):

$$Q = 4\pi K_e(t + b - r)/gL \qquad 2.2$$

where:

$$g = 2\ln\left(\frac{\tan(\pi(2d - r)/4h)}{\tan(\pi r/4h)}\right) \qquad 2.3$$

h is the depth of soil profile (cm); r is the radius of the drain tube (cm); t is the depth of water on the soil surface (cm); b is the depth to the drains (cm); and other parameters were described in Equation 2.1. One of the planned modifications of the WEPP hillslope model is to add the Kirkham equation to the drain flow prediction algorithms. Before these modifications are made, a study of the contribution of the Kirkham equation on drain flow predictions was needed. Any applicability of the WEPP model predictions for water table managed conditions should be evaluated against field data.

This chapter describes a series of background studies thought to be interesting and necessary towards the improvement of the predictive capability of WEPP. The overall purpose of this chapter is to conduct the necessary background work to prepare input, output, and field data to be used to evaluate the WEPP-WTM model. Of particular interest are model improvements for croplands where subsurface drainage, controlled drainage, and subirrigation are used. The specific objectives of the work presented herein are:

1) evaluate drain flow and runoff predictions using a range of saturated hydraulic conductivity test data with DRAINMOD;
2) analyze the relative impact of changes in drainage trench backfill properties on drainage flows and runoff;
3) evaluate monthly Potential EvapoTranspiration (PET) adjustment factors used in DRAINMOD for the prediction of drain flow and runoff; and
4) evaluate the effects of Kirkham-Hooghoudt equations on drain flow and runoff prediction accuracy of DRAINMOD against an empirical equation and determine the relative contribution of the Kirkham equation to drain flow predictions compared to the Hooghoudt equation.

2.2 LITERATURE REVIEW

2.2.1 Saturated Hydraulic Conductivity

Saturated hydraulic conductivity (K_{sat}) is a parameter to which many water table management models are very sensitive. In sensitivity analyses of DRAINMOD reported by Workman et al. (1986), saturated hydraulic conductivity ranked second behind PET adjustment factors in having the greatest effect on model results.

There are many field and laboratory methods to estimate K_{sat} (Amoozegar and Warrick, 1986; Klute and Dirksen, 1986). One widely used laboratory method for determining hydraulic conductivity is the core method (Klute and Dirksen, 1986). Skaggs (1980) states that K_{sat} values determined from cores tend to be smaller than field values because the cores usually do not contain cracks, worm-holes, etc. Skaggs (1980) also mentioned that these values usually represent vertical K_{sat} while drainage flows depend more on horizontal K_{sat}.

The auger hole method (Bouwer and Jackson, 1974) is an easy, fast, and widely used field method to determine horizontal K_{sat}. For layered soils, Bouwer and Jackson (1974) stated that an estimate of K_{sat} for each layer can be obtained by using the same hole for different water-table positions. They referenced van Beers (1970) for more detailed discussion and usage of this method. To evaluate DRAINMOD for a Commerce clay loam soil in the Lower Mississippi Valley, Fouss et al. (1987) used the auger hole method to determine effective horizontal saturated hydraulic conductivity (K_e) values. Workman et al. (1986) recommended the auger hole and well permeameter methods to obtain field hydraulic conductivity values for DRAINMOD.

Another method to determine hydraulic conductivity is based on the use of steady state drainage equations with measured water table depths and corresponding drain flows. Hoffman (1963) used equations of Glover (as reported by Dumm, 1959), van Schilfgaarde (van Schilfgaarde, 1963), Hooghoudt (Hooghoudt, 1940), and Kirkham (Kirkham, 1957) to calculate equivalent saturated hydraulic conductivity (K_e) values from drain outflow and water table drawdown data from a drainage experiment (Schwab et al., 1963; 1975; and 1985) at the North Central Branch of the Ohio Agricultural Research and Development Center (OARDC), near Sandusky, Ohio. The form of the Glover equation (as reported by Dumm, 1959) used by Hoffman (1963) is:

$$K_e = \frac{QL^2 \ln\left(\frac{4H_i}{\pi H}\right)}{\pi^2 \left(D + \frac{H_i}{2}\right)(H_i - H)} \quad \ldots\ldots\ldots\ldots\ldots\ldots 2.4$$

where: K_e is the equivalent saturated hydraulic conductivity (cm/day); Q is the drain flow depth (cm/day); L is the drain spacing (cm); H_i is the midspace water table elevation before a short drop in the water table; H is the midspace water table elevation (cm) above the drain; and D is the depth from the drain center to the impermeable layer (cm). The form of the van Schilfgaarde equation (van Schilfgaarde, 1963) used by Hoffman (1963) was:

$$K_e = \frac{2QS^2}{9A^2 (d_e + H)(d_e + H_0)} \quad \ldots\ldots\ldots\ldots\ldots\ldots 2.5$$

where: K_e is the equivalent saturated hydraulic conductivity (cm/day); d_e is the equivalent depth from the drain to the impermeable layer (cm); H_0 is the initial midspace water table elevation (cm) above drain; L is drain spacing (cm); H is midspace water table elevation (cm) above drain; and A is constant defined by Hoffman and Schwab (1964):

$$A = \left[1 - \left\{ \frac{d_e}{d_e + H_o} \right\}^2 \right]^{1/2} \quad \ldots\ldots 2.6$$

The form of the Hooghoudt equation used by Hoffman (1963) was shown earlier as Equation 2.1. The form of the Kirkham equation given by Hoffman (1963) was:

$$H = (\frac{LQ}{\pi K_e})(\frac{1}{1 - \frac{Q}{K_e}})[\ln \frac{L}{\pi r} + \sum_{j=1}^{\infty} \frac{1}{j}(\cos \frac{2j\pi r}{L} - \cos j\pi)(\coth \frac{2j\pi(H + D)}{L} - 1] \ldots\ldots 2.7$$

where: r is the drain radius (cm); and all other parameters were described earlier. Since Equation 2.7 can not be solved explicitly for K_e, graphs published by Toksoz and Kirkham (1961) were used by Hoffman (1963) to determine equivalent saturated hydraulic conductivity (K_e) values. In addition to the above K_{sat} estimation methods, Skaggs (1976) presented a field method to determine effective horizontal K_{sat} values from water table drawdown or water table rise measurements.

2.2.2 Monthly PET Adjustment Factors

PET adjustment factors are an important input parameter affecting the prediction of outflows in DRAINMOD. In DRAINMOD, two options are available for estimating PET. The user can create an input PET file or a daily minimum and maximum temperature data file. If temperature data files are used, then DRAINMOD computes PET using Thornthwaite's (1948) equation. The Thornthwaite PET estimates can be adjusted on a monthly basis if more reliable average values for crop-ET are known (Workman et al., 1986). However, studies have shown that the Thornthwaite's equation underestimated PET during winter months and overestimated it during the summer months at Kimberly-Idaho, Coshocton-Ohio, and eastern North Carolina (Jensen et. al., 1990; Mohammad, 1978).

For Louisiana conditions, Fouss et al. (1987) used PET adjustment factors, which essentially flattened the PET curve by exceeding the Thornthwaite PET during the winter months and then reducing it during growing season. For eastern North Carolina conditions, Amatya et al.

(1992; 1995) determined PET factors by dividing monthly PET values estimated by the Penman-Monteith method (Jensen et al., 1990) by those calculated using the Thornthwaite method (Thorntwaite, 1948). To determine daily PET values using the Penman-Monteith method, Amatya et al. (1992 and 1995) used a program called REF-ET (Version 2.0) (Allen, 1990). To calculate daily PET values using the Thornthwaite method, they wrote a simple fortran program (Amatya et al., 1992). A similar analysis to determine PET adjustment factors for Ohio conditions was attempted by Patterson et al. (1997), but they stated that no adjustment factors would be used in their study, and that more work was needed to better justify the use of PET adjustment factors for Ohio conditions.

2.3 MATERIALS AND METHODS

2.3.1 Background of Research Site for Measured Flow Data

At the OARDC North Central Branch, near Sandusky, Ohio, runoff and drain flow volumes were measured for the period March 1 to September 30 each year starting in 1958 until 1980 (Schwab et al., 1963; 1975; and 1985). The experiment consisted of four replicates for four treatments: no drainage, surface drainage only, subsurface drainage only, and a combination of subsurface and surface drainage. The plot size was 0.22 ha (0.55 ac) with the dimensions of 37 by 61 m (120 by 200 ft). To prevent runoff and soil water movement between plots, each plot was surrounded with a 15 cm (6 in) high earthen dike on the surface and 120 cm (48 in) deep plastic barriers. Three drainage laterals were installed in each plot, and drain flows were measured from the middle lateral. The drains were 10 cm (4 in) concrete tile with spacers on one end so as to provide a uniform slit space between tiles of about 0.32 cm (0.125 in). The predominant soil type (about 80% of areal coverage) at the site was Toledo silty clay.

Runoff and drain flow data for eight years (1962-64 and 1967-71) from this site were used in this research because the same crop (corn) was grown during these years. There is a break in plot crop-management in 1965 and 1966. Soybean and oats were grown at the site in 1965 and 1966, respectively. Because of the starting inconsistency of outflow measurements made in March as stated by Skaggs et al. (1981), this evaluation is based on the data from April 1 to September 30 each year. Hourly precipitation, and daily maximum and minimum temperatures were recorded at the site. Irrigation water was applied twice each year in May, June, or July to provide a repeatable 10-year return period storm. Detailed information about this research site, field measurements, hydrologic and crop results can be found in Schwab et al. (1963; 1975; and 1985)[1].

2.3.2 Evaluation Procedure

In this study, to calculate average deviations between the predicted and measured drain flows and runoff, DRAINMOD (version 4.6) predicted runoff and drain flow depths were used with the measured runoff and drain flow depths from the combination plots (surface and subsurface drained)[2]. The combination plots described by Schwab et al. (1963; 1975; and 1985) were chosen because of the availability of both runoff and drain flow measurements from these plots. There were no continuous water table depth measurements on these plots.

The agreement between predicted and measured values was quantified on the basis of daily and cumulative values for the test years (1961-1964; 1967-1971) by computing average deviation (cm) within each year as:

$$average\text{-}deviation = \sum_{i=1}^{n} |x_i - y_i| / n \qquad 2.8$$

where: x_i is the predicted daily drain flow or runoff depth; y_i is the measured daily drain flow or runoff depth on day i; and n=183, the number of days in the simulation period (April 1 to September 30). Equation 2.8 was also used to calculate the agreement between cumulative predicted and measured outflows. In this situation, starting from April 1 ($i = 1$), x_i is the predicted cumulative drain flow or runoff volume; and y_i is the measured cumulative drain flow or runoff volume on day i. In 1964, the sprinkler irrigation system at the site was enlarged to cover two replications at one setting. Therefore, DRAINMOD was run for each individual replication until the 1964 growing season. For 1964 and thereafter, DRAINMOD was run for the mean of the two replications because same weather data was used for both replications that were irrigated at the same time with the same amount of irrigation water.

---

[1] : In 1983, the ownership of the site was given to the Ohio Department of Natural Resources. The site is now being protected as a wildlife area.

[2] : The data from this site were used to evaluate DRAINMOD for North Central Ohio conditions by Skaggs et al. (1981) and to evaluate the ADAPT model (Chung et al., 1992). The version of DRAINMOD described by Skaggs (1980) and used by Skaggs et al. (1981) did not contain algorithms for the drainage coefficient (DC) and Kirkham's depth (STORRO).

2.3.3 Input Data

For the current study, the same general subsurface drainage system parameters and values used by Skaggs et al. (1981) were used except saturated hydraulic conductivity values (K_{sat}) and equivalent depth from the drain to the impermeable layer (d_e). The input values of subsurface drainage system parameters used in this study are listed in Table 2.1 and illustrated in Figure 2.1. A 75 cm (29.5 in) value for the equivalent depth from the drain to the impermeable layer was used by Skaggs et al. (1981). DRAINMOD (Version 4.6) now estimates a value for the parameter d_e using the following equations (Skaggs, 1980):

for $0 < d/L < 0.3$;

$$d_e = \frac{d}{1 + \frac{d}{L}\left(\frac{8}{\pi}\ln\left(\frac{d}{r_e}\right) - \alpha\right)} \quad \text{.......... 2.9}$$

where: d_e is the equivalent depth from the drain to the impermeable layer (cm); d is the depth from center of the drain to the impermeable layer (cm); L is the drain spacing (cm); r_e is the effective radius of the drain tubes (cm); and α is a parameter calculated using equation (Skaggs, 1980):

$$\alpha = 3.55 - \frac{1.6d}{L} + 2\left(\frac{2}{L}\right)^2 \quad \text{.......... 2.10}$$

for $d/L \geq 0.3$;

$$d_e = \frac{L\pi}{8\left(\ln\left(\frac{L}{r_e}\right) - 1.15\right)} \quad \text{.......... 2.11}$$

A value of 47.52 cm (18.7 in) for d_e was predicted by DRAINMOD (Version 4.6) and used in this study in place of the 75 cm used by Skaggs et al. (1981). The soil water retention data were obtained from field experiment notes of Schwab et al. (1963; 1975; and 1985) and data presented by Skaggs et al. (1981) (Appendix A, Figure 1). The relationships between water table depths

Parameter	Value (cm)
Drain spacing	1220
Drain depth	90
Equivalent depth from drain to impermeable layer	47.52
Estimated profile depth	165
Depth of surface storage	0.25
Kirkham's depth (STORRO)	0.1
Drain diameter	10

Table 2.1. Summary of drainage system input parameters used in DRAINMOD for Toledo silty clay at the OARDC North Central Branch, near Sandusky, Ohio (Schwab et al., 1963; 1975; and 1985).

versus drained volumes, upward fluxes, and Green-Ampt equation parameters were taken from data developed by Skaggs et al. (1981) (Appendix A, Figures 2 and 3; and Table 2).

DRAINMOD (Version 4.6) now uses a Kirkham's depth (STORRO) and drainage coefficient (DC) compared to the version described by Skaggs (1980) and used by Skaggs et al. (1981). The Kirkham's depth is used to determine whether the model uses Hooghoudt's or Kirkham's equation when water table depth is less than 0.5 cm (0.2 in) from the soil surface. In this study, a value of 0.1 cm (0.04 in) was used for STORRO based upon the fact that the field data were collected on plots that were surface drained at 0.2% slope.

The parameter DC is used as the hydraulic capacity or design flow capacity of the drain. In DRAINMOD, drain flow predicted by the Kirkham and Hooghoudt equations is limited to the value of DC. Workman et al. (1986) suggested using a DC value of 2 cm/day (0.8 in/day) for a 10 cm (4 in) dia. drainage pipe especially if a drainage system is being designed using DRAINMOD. In the current study, a DC value of 5.3 cm/day (2.1 in/day) was determined using the following empirical equation (English units) for the case where the water table was at the soil surface at the midspace between two drains (Hoffman, 1963):

$$Log Q = 0.48H^2 - 0.54H - 2.27 \qquad 2.12$$

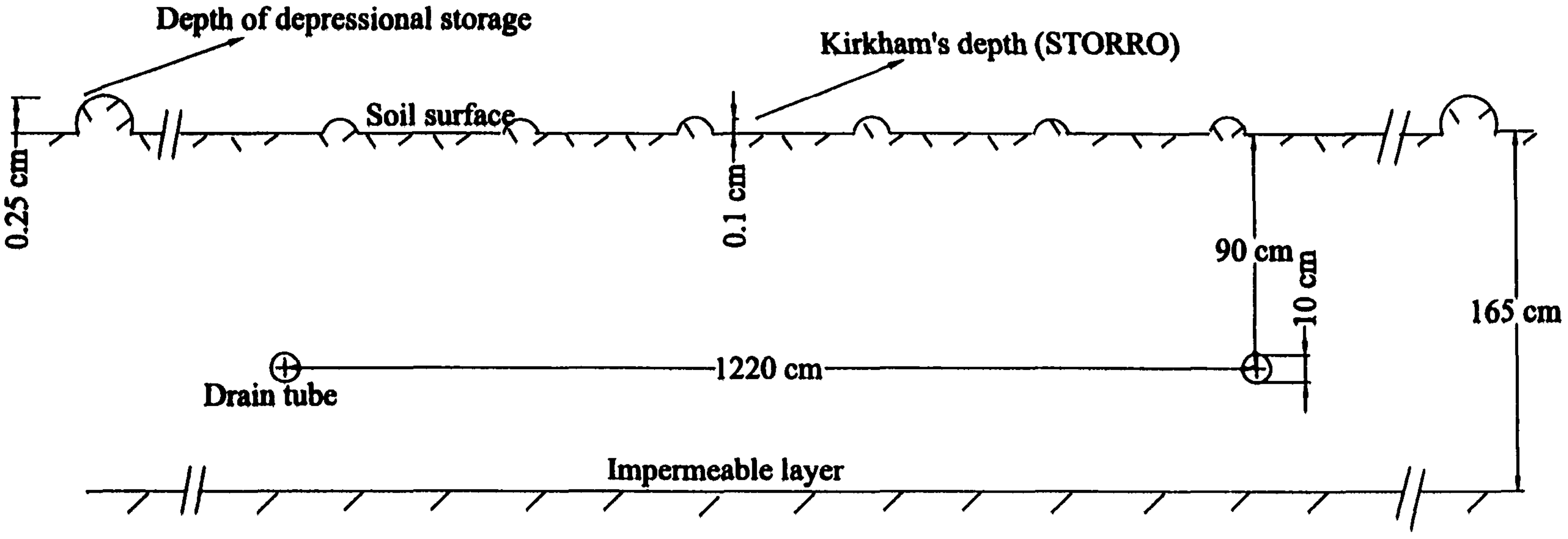

Figure 2.1 Subsurface drainage system input parameters (from Table 2.1) used in DRAINMOD for Toledo silty clay at the OARDC North Central Branch, near Sandusky, Ohio (Schwab et al., 1963; 1975; and 1985).

where: Q is drain flow depth (in/day); and H is midspace water table elevation (ft) above the drain. The metric unit form of Equation 2.12 is:

$$LogQ = \frac{H^2}{1935.42} - \frac{H}{56.44} - 1.865 \quad \text{..........} \quad 2.13$$

where: Q is drain flow depth (cm/day); and H is midspace water table elevation (cm) above the drain. Assuming for the current study that the midspace water table elevation was a maximum at 90 cm (2.95 ft), the DC would correspond to the flow calculated at the maximum elevation using Equation 2.13.

Equation 2.12 was found as the best empirical solution by Hoffman (1963) using data[3] from the combination plots (surface and subsurface drained) at the drainage experiment described by Schwab et al. (1963; 1975; and 1985). This equation was developed using the measured midspace water table elevations above the drain and the corresponding drain flow rates for the years of 1960, 1961, and 1962.

2.3.4 Saturated Hydraulic Conductivity

Since drainage and subirrigation usually involve lateral flow to and from drains, the horizontal K_{sat} values are preferable for use in DRAINMOD and other water table management models. Skaggs (1980) states that horizontal and vertical K_{sat} may differ by a factor of 10. Since horizontal K_{sat} values are not always available, vertical K_{sat} values are used in place of horizontal K_{sat}, with the assumption that they are equal. In addition, if there are no measured K_{sat} values, some soil database programs such as the MUUF (Map Unit Use File) soil database (Baumer, 1989) can be used to obtain an estimate of K_{sat}.

In this research, the average deviations between the predicted and measured outflows were used to determine the most suitable K_{sat} values as input into DRAINMOD, and subsequently other water table management models. DRAINMOD (Version 4.6) was run for seven different K_{sat} data sets, based on seven different methods of estimating K_{sat} values. The K_{sat} methods evaluated were: monolith method (Taylor et al., 1970), core method (Klute and Dirksen, 1986), MUUF soil database (Baumer, 1989), auger hole method (Bouwer and Jackson, 1974), and using the Hooghoudt, Kirkham, and van Schilfgaarde equations with water table drawdown

---

[3] : These data were collected as part of Hoffman's (1963) thesis research at the drainage experiment described by Schwab et al. (1963; 1975; and 1985).

and drainage flow data. The vertical saturated hydraulic conductivity values from the monolith and core methods were used as horizontal K_{sat} values.

Since this evaluation used data from the combination plots of Schwab et al. (1963; 1975; and 1985), Equation 2.12 was used to calculate drain flows for different midspace water table elevations above drain. These midspace water table elevations and the calculated drain flows are given in Table B1 (Appendix B), and were derived from the soil horizon data (Appendix C, Table A1) given by Schwab et al. (1963). The drain flows were then used to estimate the equivalent saturated hydraulic conductivity (K_e) values in Table B1 using the van Schilfgaarde (Eq. 2.5) and Hooghoudt (K_e derived form of Eq. 2.1) equations, and Kirkham approach. To estimate equivalent K_e values using the Kirkham approach, graphs for the Kirkham equation developed by Toksoz and Kirkham (1971) (Appendix D, Figure 1 with example calculation) were used in place of the Kirkham equation (Eq. 2.7). The equivalent depth (d_e) to be used in the Hooghoudt and van Schilfgaarde equations was calculated using Equation 2.9. The value of the initial water table depth[4] (94 cm; 3.1 ft) used in Equations 2.5 and 2.6 was taken from Hoffman (1963) (Appendix E, Table 7). The calculated equivalent hydraulic conductivity values for the water table depths used in this analysis are given in Table 2.2.

Other estimates of hydraulic conductivity at this site were obtained by the Ohio Soil Survey personnel (Ohio Soil Survey, 1960), Schwab et al. (1963), and Taylor et al. (1970). The Ohio Soil Survey personnel conducted auger hole tests at the drainage experiment of OARDC North Central Branch, during the period 9/13-19/1960. Nine auger holes, three for each depth increment 0.0-30.5, 30.5-61, and 61-91 cm (0-12, 12-24, and 24-36 in) were studied on the surface drainage only plot at this site. The average horizontal hydraulic conductivity values from three holes for each of these three depth increments are given in Table 2.3. The conductivity values for the 91-165 cm (36-65 in) depth increment were abstracted from Skaggs et al. (1981). Also, vertical K_{sat} values for each of the eight soil horizons at the site were determined by Schwab et al. (1963) using six standard 7.6 cm (3 in) dia. cores for each horizon. Taylor et al. (1970) used undisturbed, rectangular cross-sectioned soil monoliths (152 by 152 by 183 cm) (5 by 5 by 6 ft) to determine vertical K_{sat} values of the soil at this site. The monolith method K_{sat} values were used in the evaluation study of the ADAPT model. Alexander (1988) stated that the ADAPT model tends to underpredict drain flows and overpredict runoff.

---

[4] : The initial water table depth in the equations used by Hoffman (1963) is the distance between the surface and the bottom of tile (94 cm). However, the water table depth in DRAINMOD is being simulated from the center line of the drain (90 cm).

Midspace Water Table Depth (cm)	Analytical Methods Using Drain Outflow Data		
	van Schilfgaarde	Hooghoudt	Kirkham
0.00	5.518	6.208	10.483
15.24	0.552	0.723	1.120
30.48	0.097	0.153	0.217
45.72	0.031	0.061	0.077
71.02	0.016	0.064	0.067
101.60*	0.01	0.01	0.01
165.00*	0.01	0.01	0.01

*: Conductivity values for these two water table depths were originally taken from Hoffman and Schwab (1964) by Skaggs et al. (1981). They are based on field measured drain flow and corresponding midspace water table depths from the drainage experiment at the OARDC North Central Branch (Schwab et al., 1963; 1975; and 1985).

Table 2.2. Equivalent saturated hydraulic conductivity values (K_e) of Toledo silty clay as a function of water table depth from the soil surface. These conductivity values were calculated using the van Schilfgaarde and Hooghoudt equations (Eq. 2.5 and 2.1, respectively) and the Kirkham approach described by Toksoz and Kirkham (1971).

Soil Profile Depth (cm)	Hydraulic Conductivity (cm/hr)
0 - 30.5	25.50
30.5 - 61.0	9.16
61.0 - 91.5	0.20
91.5 - 165.0	0.01*

*: Conductivity value for this soil profile depth interval was originally taken from Hoffman and Schwab (1964) by Skaggs et al. (1981). This is based on field measured drain flow and corresponding midspace water table depths from the drainage experiment at the OARDC North Central Branch (Schwab et al., 1963; 1975; and 1985).

Table 2.3. Saturated horizontal hydraulic conductivity (K_{sat}) values (Ohio Soil Survey, 1960) for Toledo silty clay at the OARDC North Central Branch, near Sandusky, Ohio using the auger hole method.

To use any of the saturated hydraulic conductivity data sets presented above as input to DRAINMOD (Version 4.6), horizontal saturated hydraulic conductivity values (K_{sat}) of each soil layer must be entered with each layer's specific bottom depth. The equivalent saturated hydraulic conductivity values (K_e) given in Table 2.2 were converted to layer specific horizontal saturated hydraulic conductivity values (K_{sati}) using the following form of Equation 2.16 given by Skaggs (1980):

$$K_{sati} = \frac{K_e \Sigma D_i - \Sigma K_{sati-1} D_{i-1}}{D_i} \quad \text{.......} 2.14$$

where: D_i is the thickness of soil layer i; and other parameters were already described. The assumption that the lowest layer's equivalent saturated hydraulic conductivity (K_e) value was equal to the lowest layer's horizontal K_{sat} value was used in this conversion and the conversion operation was started from the lowest layer and continued to the next lower layer, and so forth to the top soil layer. The horizontal K_{sat} values from all the considered methods are given in Table 2.4. Except for the horizontal hydraulic conductivity data obtained from the MUUF soil database, all the conductivity values relate to the same depth increments. All of these values are in an appropriate form to be used as input to DRAINMOD (Version 4.6).

Layer Depth (cm)	Analytical Methods Using Drain Outflow Data: van Schilfgaarde	Hooghoudt	Kirkham	Monolith[*] Method	Core[**] Method	Auger Hole[+] Method	MUUF Database
0-20	42.477	47.166	80.260	1.397	2.540	25.50	0.879
20-50	1.920	2.461	3.859	1.016	0.204	9.16	0.336
50-102	0.052	0.125	0.156	0.102	0.142	0.20	0.279
102-165	0.010	0.010	0.010	0.051	0.267	0.01	0.279

*: From Table 4 (given in Appendix F) by Taylor et al. (1970)
**: From Table A1 (given in Appendix C) by Schwab et al. (1963)
+: From Ohio Soil Survey (1960)

Table 2.4. Estimated horizontal saturated hydraulic conductivity (K_{sat}) values (cm/hr) for Toledo silty clay soil layers.

2.3.5 Hydraulic Conductivity Changes in Backfill

The effects of changes in the hydraulic conductivity of backfill on drain flows have been studied by only a few authors. These studies include those of Taylor and Fausey (1982) on the effects of backfill alterations on drain flow over time and the Kowald (1968) data (given by Trafford and Rycroft, 1974), which evaluated pore volume changes in the backfill over time. Both of these studies support the concept that the hydraulic conductivity of the backfill decreases over time. Therefore, using constant hydraulic conductivity values, such as those derived using the Hooghoudt, Kirkham, and van Schilfgaarde equations, in water table management models for a long period of time may not be a realistic approach for a trenched and back-filled drainage system.

For the current research, these hydraulic conductivity values were calculated using field measured drain flows and corresponding midspace water table elevations for the years of 1960, 1961, and 1962 from the drainage experiment at the OARDC North Central Branch (Schwab et al., 1963; 1975; and 1985). The concrete tiles were installed in a 40.6 cm (16 in) wide and 96.5 cm (38 in) deep ditch. The blinding for the drains was made by placing the original topsoil (which included alfalfa stems and roots) to a depth of 15 cm (6 in) above the top of the tile (Schwab et al., 1963).

Forty years after installation of the drains at this site, soil samples were taken just above the tiles to measure saturated hydraulic conductivity of the backfill. Standard 7.6 cm (3 in) dia. soil cores were taken from every 15 cm (6 in) soil depth increment using a Gidding's apparatus. In the laboratory, a constant head permeameter test was applied to measure saturated hydraulic conductivity values on these soil samples. The measured K_{sat} values from the permeameter test are given in Table 2.5 along with the data of Schwab et al. (1963) (Appendix C, Table A1) for the undisturbed soil profile. The 1998 data show a decrease in conductivity down to the 60 cm (23.6 in) depth compared to the Schwab et al. (1963) data.

To measure the characteristics of drain flow as related to backfill alterations, Taylor and Fausey (1982) conducted an experiment during 1978 through 1982 on two previously mentioned plots (no drainage) at the OARDC North Central Branch. In 1969, 4.2 cm (1.65 in) dia. corrugated plastic tubing was installed on these plots to an average depth of 40 cm (15.7 in) and at a spacing of 6.1 m (20 ft) using a floating-beam mole plow. Taylor and Fausey (1982) conducted the study in the backfill above these plastic tubes. After drain installation with the plow, they excavated a 15 cm (6 in) wide trench over the entire 61 m (200 ft) length of the drain

Core (1963)⁺ (Original undisturbed site data)		Recent Core Data (1998)* (Backfill)	
Depth (cm)	K_{sat} (cm/hr)	Depth (cm)	K_{sat} (cm/hr)
0-20	2.540	0 – 33	1.541
20-33	0.296	33 – 46	0.016
33-51	0.138	46 – 61	0.063
51-76	0.095	61 – 75	0.193
76-96	0.169	75 – 96	0.307

+: Core samples collected and analyzed by Schwab et al. (1963) (Appendix C, Table A1) for undisturbed soil.

*: Core samples collected from the trench backfill in 1998, 40 years after tile installation.

Table 2.5. Saturated hydraulic conductivity (K_{sat}) values of Toledo silty clay at the OARDC North Central Branch.

lateral to an average depth of 5 cm (2 in) above the drain. Then, they back filled with excavated soil. Twice annually, these plots were ponded by applying excess water with sprinkler irrigation and the maximum drain flows were measured. The maximum drain flow (m^3/day) versus year data presented by Taylor and Fausey (1982) (Appendix G, Figure 3) were obtained for the current study, and these data were then used to develop the following equation (using Microsoft Excel):

$$y = 0.399x^{-0.5389} \quad \text{..........} 2.15$$

where: y is maximum drain flow (m^3/day); and x is the year of interest after the installation of a trenched and back filled subsurface drainage system. For the purpose of the current research, the units of flow of m^3/day as presented by Taylor and Fausey (1982) were maintained Figure 2.2 shows the fit of Equation 2.15 to the observed data for two years after installation of this subsurface drainage system.

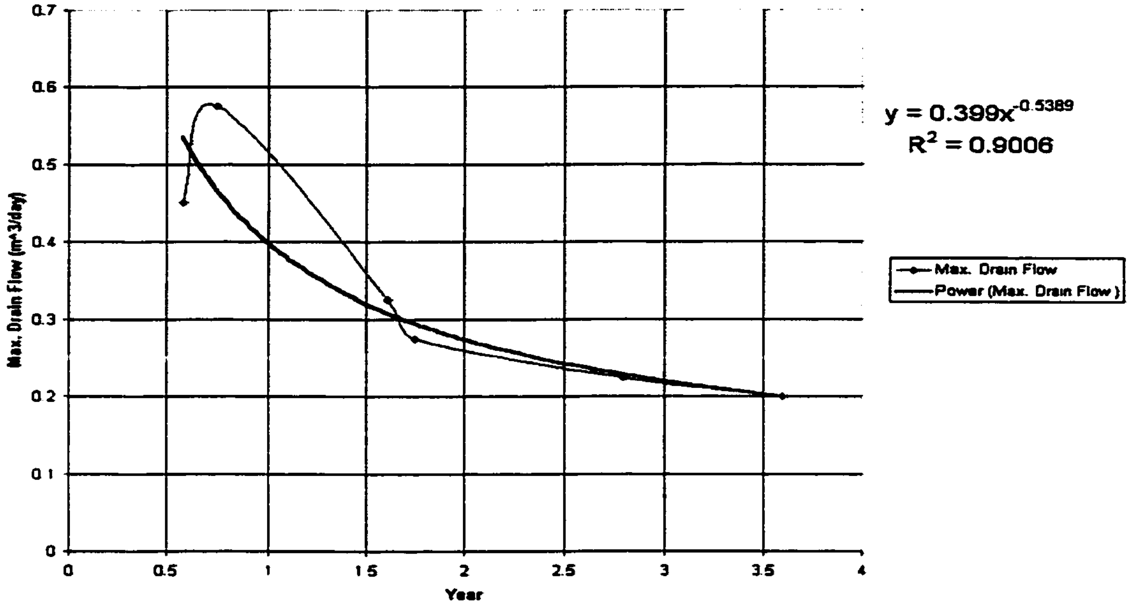

Figure 2.2 Maximum drain flow with time after installation of backfill experiment conducted at the OARDC North Central Branch, near Sandusky, Ohio, by Taylor and Fausey (1982), 1978 through 1982. The top curve was taken from the data of Taylor and Fausey (1982) (Appendix G, Figure 3). The bottom curve is presented as equation 2.15.

Assuming that most of the measured drainage and runoff flows from the Schwab et al. (1963; 1975; and 1985) study were from the constant intensity-irrigation events, the ratios of measured drain flow and runoff to measured rainfall were calculated. These ratio data (Figure 2.3) illustrates that in time the rate of runoff increased until 1970. Interestingly enough, changes in the rate of drain flow with time (Figure 2.3) followed a pattern similar given previously by Taylor and Fausey (1982) (Appendix G, Figure 3) except after the seventh year. In the Taylor and Fausey (1982) study, drain flow increased for up to one year, then began to decrease. For the Schwab et al. (1963; 1975; and 1985) data, drain flow rates increased just after installation of backfill until 1964, then began to decrease. The decrease in drain flows is most likely because of the decrease of hydraulic conductivity in the backfill. Furthermore, increased runoff over time may have partially resulted from a reduction in surface water flow into the drains through the backfill over time, and subsequently because of the decreased hydraulic conductivity of backfill in time. Perhaps the

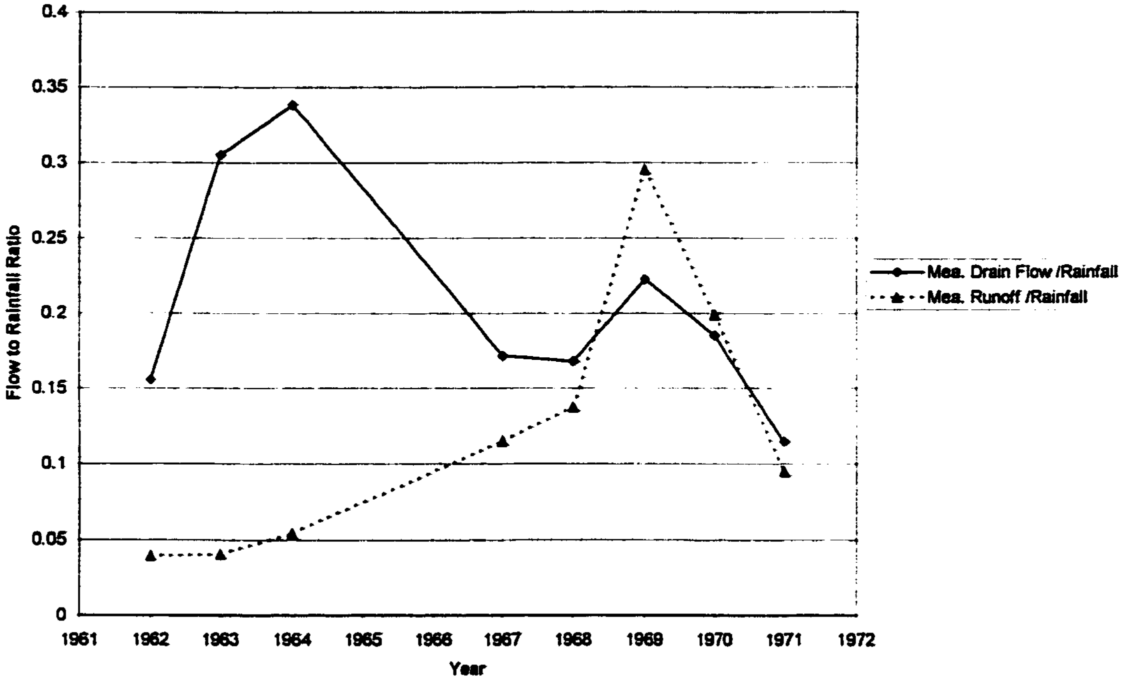

Figure 2.3. The ratios of measured drain flows and runoff to measured rainfall at the OARDC North Central Branch, during the years 1962-1971.

application of excess irrigation water every year at the site accelerated soil consolidation, and the natural decrease of hydraulic conductivity in the backfill.

Equation 2.15 will later be used to adjust K_{sat} values selected for the drain flow and runoff simulations explained in the previous section. In applying, Equation 2.15, it was assumed that decreased hydraulic conductivity in the backfill affected soil layers' effective hydraulic conductivity values as well. To measure the effects of hydraulic conductivity changes in the backfill on drain flow and runoff predictions, these adjusted K_{sat} values will also be used in DRAINMOD runs. Average deviations between predicted and field measured drain and runoff flows will also be calculated.

2.3.6 Monthly PET Adjustment Factors

In a previous evaluation of DRAINMOD for Ohio conditions (Skaggs et al., 1981), the PET adjustment factor was not used because the version of DRAINMOD at that time did not include this adjustment. For the current research, an approach similar to that described by Amatya et al. (1992; 1995) was used to determine PET adjustment factors. In this analysis, daily PET values using the Thornthwaite (1948) method were calculated using the DRAINMOD (Version 4.6) fortran source code, and the daily PET values using the Penman-Monteith (Monteith, 1981) method were calculated using the DAILYET model (Hess, 1999) developed at Cranfield University. PET values predicted using the DAILYET model were checked with the results produced with the REF-ET program (Version 2.15a) (Allen, 1994). As mentioned before, the REF-ET program was used by Amatya et al. (1992; 1995). Both methods produced the same monthly PET values.

Nokes (1995) stated that the Thornthwaite (1948) equation is an empirical formula based on temperature. Maximum and minimum temperature data are available at a large number of localities, which enables the method to be widely used. The Penman-Monteith method is based on the combination of the energy balance and aerodynamic equations (Jensen et al., 1990). Detailed descriptions of these methods can be found in Jensen et al. (1990). The DAILYET model uses the Penman-Monteith method which was ranked first among the many methods evaluated by Jensen et al. (1990).

The Thornthwaite's method required daily maximum and minimum temperatures were measured at the site and these values were obtained from the field experiment notes. In addition to these temperature data, the Penman-Monteith method also needs daily net solar radiation, relative humidity, and wind speed. These data were obtained from the Midwestern Climate Data Center[5] (MCDC) for Toledo, Ohio, which is approximately 65 km (40.4 mi) west-north west from the OARDC North Central Branch site. Daily solar radiation was converted into daily net radiation using the following equation (Jensen et al., 1990):

$$R_n = (1-\alpha)R_s - R_b \quad \text{.......} 2.16$$

where: R_n is the daily net radiation (MJ/m^2); α is the albedo (dimensionless and assumed as equal 0.23, which is generally used for most green field crops with a full cover); R_s is the daily received solar radiation (MJ/m^2) and R_b is the net outgoing thermal radiation (MJ/m^2). The daily

---

[5]: Illinois State Water Survey, 2204 Griffith Drive, Champaign, IL 61820-7495

PET values predicted using the Thornthwaite and Penman-Monteith methods were then summed to obtain monthly PET values. To determine the monthly PET adjustment factors, the monthly Penman-Monteith PET values were divided by the monthly Thornthwaite PET values.

This PET factor analysis covered only the months corresponding to the drain flow and runoff data used in this study. The remaining months (October-March) were not included mainly because of the following reasons: i) DRAINMOD was developed for warm humid climates and was not tested for winter months of cold humid climates; and ii) the Thornthwaite method used in DRAINMOD produces zero PET values for days when the temperature is below 0 °C (32 °F), while, the Penman-Monteith method produces some PET values.

2.3.7 Evaluation of Kirkham-Hooghoudt Equations on Drain Flow and Runoff Predictions Using DRAINMOD

DRAINMOD was used to evaluate the accuracy of the Kirkham-Hooghoudt equations on drain flow and runoff prediction compared to Equation 2.12 for a layered soil. An assumption was made that Equation 2.12 best describes the water table depth-drain flow relationship expressed by the data at the experimental site. In the DRAINMOD source code, Equation 2.12 was used in place of the Kirkham and Hooghoudt equations, and then predicted drain flows and runoff were compared with the original DRAINMOD (with Kirkham-Hooghoudt equations) predicted drain flows and runoff (described in Section 2.3.4 'Saturated Hydraulic Conductivity').

In addition, DRAINMOD was run with the Hooghoudt equation used in place of the Kirkham-Hooghoudt equations to determine the relative contribution of the Kirkham equation on drain flow prediction. Predicted drain flows and runoff were compared with the original DRAINMOD (with Kirkham-Hooghoudt equations) predicted and measured drain flows and runoff.

In summary, the analyses performed in Sections 2.3.4 through 2.3.7 are summarized in Table 2.6. This summary helps to explain which results from early analyses are then subsequently used in the later analyses.

2.3.4 Saturated Hydraulic Conductivity
  - A-There is no change in DRAINMOD source code
  - B-Use 1.0 as monthly PET adjustment factors in DRAINMOD
  - C-Use 5.3 cm/day (2.1 in/day) as Drainage Coefficient (DC) in DRAINMOD
  - D-Run DRAINMOD for seven different K_{sat} data sets

2.3.5 Backfill Hydraulic Conductivity Changes in Backfill
  - A-Same as previous analysis
  - B-Same as previous analysis
  - C-Same as previous analysis
  - D-After determining the best K_{sat} method in section 2.3.4, adjust the K_{sat} values in this best method using Equation 2.12, and use these adjusted K_{sat} values

2.3.6 Monthly PET Adjustment Factors
  - Scenario I:
    - A-Same as previous analysis
    - B-Determine monthly PET adjustment factors in this section and use these determined monthly PET adjustment factors in DRAINMOD
    - C-Same as previous analysis
    - D-Use the K_{sat} values of best K_{sat} method determined in section 2.3.4
  - Scenario II:
    - A-Same as previous analysis
    - B-Same as previous analysis
    - C-Same as previous analysis
    - D-Same as in Section 2.3.5

2.3.7 Evaluate Effects of Kirkham-Hooghoudt Equations on Drain Flow and Runoff Prediction Accuracy of DRAINMOD
  - Scenario I:
    - A-Change DRAINMOD source code (use Equation 2.7 in place of Kirkham-Hooghoudt equations in DRAINMOD source code)
    - B-Same as in Section 2.3.4
    - C-Same as in Section 2.3.4
    - D-Same as in scenario I in Section 2.3.6
  - Scenario II:
    - A-Same as previous analysis
    - B-Same as in Section 2.3.4
    - C-Use 10 cm/day (4 in/day) as Drainage Coefficient (DC)
    - D-Same as in scenario I in Section 2.3.6
  - Scenario III:
    - A-Change DRAINMOD source code (use only Hooghoudt equation in place of Kirkham-Hooghoudt equations)
    - B-Same as in Section 2.3.4
    - C-Same as previous analysis
    - D-Same as in scenario I in Section 2.3.6

Table 2.6. The performed analyses in sections 2.3.4 through 2.3.7 described in Material and Methods.

2.4 RESULTS AND DISCUSSION

This section covers the results and discussion of the following subjects: i) hydraulic conductivity evaluations; ii) hydraulic conductivity changes in backfill; iii) monthly PET adjustment factors; and iv) evaluation of the Kirkham-Hooghoudt equations on drain flow and runoff predictions using DRAINMOD.

2.4.1 Hydraulic Conductivity Evaluations

The results of the hydraulic conductivity analyses shown in Tables 2.7 and 2.8, are the average daily and cumulative deviations, respectively, between measured and predicted drain flow and runoff for the eight years 1962-1964 and 1967-1971, with totals over the eight years. As mentioned before, this study covers the years during which corn was grown at the drainage experiment site (Schwab et al., 1963; 1975; and 1985).

The annual values in these tables are the means of the average deviations for each of the seven K_{sat} estimation methods for each replicate plot (Appendix H, Tables H.1 and H.2). The minimum average daily deviation for each year is underlined in Tables 2.7 and 2.8. The results in Table 2.7 suggest that no one method provided the smallest deviation in outflows when we consider the individual years, except for drain flow in 1967-1971. For each of these five years, the simulation results with the van Schilfgaarde equation estimated K_{sat} values produced the smallest average deviation. However, when we consider the total deviation over all eight years, the simulation results with the van Schilfgaarde equation estimated K_{sat} values produced the smallest total average deviations for both drain flow and runoff. The rank order of the K_{sat} methods, which produced smallest to largest total deviations in drain flow is van Schilfgaarde, Hooghoudt, and Kirkham equations estimated K_{sat} methods, auger hole, monolith, core, and MUUF soil database based K_{sat} methods. The rank order of the K_{sat} methods, which produced smallest to largest total deviations in runoff is van Schilfgaarde, Hooghoudt, and Kirkham equations estimated K_{sat} methods, auger hole, MUUF soil database, core, and Monolith based K_{sat} methods. It should be noted that the van Schilfgaarde equation estimated K_{sat} simulations also produced the smallest deviation in runoff in three of the five years with the smallest drain flow deviation. Therefore, the simulations using the van Schilfgaarde equation estimated K_{sat} values produced the smallest deviation in both drain flow and runoff for three of the eight years (37.5%).

	Analytical Methods Using Drain Outflow Data						Monolith Method		Core Method		Auger Hole Method		MUUF Soil Database	
	Van Schilfgaarde		Hooghoudt		Kirkham									
Year	Drain flow	Runoff	Drain flow	Runoff	Drain flow	Runoff	Drain flow	Runoff	Drain flow	Runoff	Drain flow	Runoff	Drain flow	Runoff
1962	0.048	0.012	0.048	0.012	0.056	0.010	0.045	0.017	0.046	0.016	0.052	0.011	0.045	0.016
1963	0.044	0.007	0.044	0.006	0.044	0.007	0.055	0.013	0.054	0.012	0.042	0.005	0.055	0.012
1964	0.069	0.010	0.067	0.010	0.075	0.009	0.078	0.029	0.077	0.026	0.078	0.012	0.080	0.027
1967	0.039	0.027	0.041	0.028	0.045	0.029	0.047	0.028	0.049	0.027	0.053	0.029	0.055	0.027
1968	0.034	0.030	0.035	0.031	0.035	0.029	0.045	0.025	0.045	0.025	0.038	0.029	0.050	0.027
1969	0.043	0.032	0.045	0.032	0.049	0.032	0.094	0.075	0.094	0.070	0.058	0.034	0.103	0.068
1970	0.055	0.047	0.057	0.048	0.067	0.054	0.085	0.055	0.087	0.053	0.062	0.050	0.096	0.047
1971	0.024	0.020	0.026	0.020	0.027	0.020	0.036	0.018	0.036	0.018	0.028	0.020	0.039	0.019
Total	0.356	0.185	0.363	0.187	0.398	0.190	0.485	0.260	0.488	0.247	0.411	0.190	0.523	0.243

Table 2.7. Means of average deviation (cm) between observed daily and predicted drain flow and runoff for seven different hydraulic conductivity value estimation methods. The observed values were obtained from the drainage experiment of OARDC North Central Branch, near Sandusky, Ohio (Schwab et al., 1963; 1975; and 1985). Average deviations for all replicates are given in Table H.1 (Appendix H). For each year, minimum mean of average deviation for drain flow and runoff is underlined.

	Hydraulic Conductivity Estimated from Drain Outflow						Monolith Method		Core Method		Auger Hole Method		MUUF Soil Database	
	Van Schilfgaarde		Hooghoudt		Kirkham									
Year	Drain flow	Runoff	Drain flow	Runoff	Drain flow	Runoff	Drain flow	Runoff	Drain flow	Runoff	Drain flow	Runoff	Drain flow	Runoff
1962	2.013	0.846	1.841	0.841	2.456	0.701	3.665	1.029	3.202	0.969	1.614	0.777	3.249	0.883
1963	5.073	0.282	4.977	0.315	4.761	0.361	5.969	0.851	5.689	0.570	4.401	0.405	5.721	0.555
1964	3.725	0.626	3.614	0.730	3.500	0.405	5.581	2.041	5.152	1.679	3.078	0.832	5.123	1.617
1967	3.817	1.822	4.075	2.075	4.485	2.424	1.396	2.043	1.329	1.719	4.699	2.440	1.451	1.507
1968	0.765	2.557	0.765	2.697	0.836	2.841	2.359	1.182	2.135	1.242	1.046	3.086	2.023	1.323
1969	3.388	2.068	3.735	1.908	4.311	1.908	4.518	8.009	3.808	7.247	4.532	1.899	3.685	7.030
1970	2.650	5.087	2.833	5.275	3.293	5.512	2.339	2.229	2.044	2.292	3.670	5.648	1.957	2.458
1971	0.813	1.616	0.826	1.739	0.907	1.902	1.837	0.990	2.008	0.955	1.063	2.049	1.948	1.005
Total	22.244	14.904	22.666	15.580	24.549	16.054	27.664	18.374	25.367	16.673	24.103	17.136	25.157	16.378

Table 2.8. Means of average deviations (cm) between cumulative daily observed and predicted drain flow and runoff for seven different hydraulic conductivity value estimation methods. The observed values were obtained from the drainage experiment of OARDC North Central Branch, near Sandusky, Ohio (Schwab et al., 1963; 1975; and 1985). Average deviations for all replicates are given in Table H.2 (Appendix H). For each year, minimum mean of average deviation for drain flow and runoff is underlined.

Figures 2.4 through 2.7 illustrate daily drain flow and runoff predictions for 1971 using the van Schilfgaarde equation estimated K_{sat} values (Figures 2.4 and 2.5) and MUUF Soil Database K_{sat} values (Figures 2.6 and 2.7). The predicted values are compared to the mean of the two individual replicates. These predictions are typical for each of these two methods. While neither of these two methods were perfect, the MUUF based K_{sat} simulations underpredicted drain flow and overpredicted runoff, sometimes by as much as 80% and 50%, respectively. For runoff, both methods produced simulation results that overpredicted runoff for at least two of the 1971 runoff events (simulation days 90 and 143), and neither predicted runoff for simulation days 54 and 55.

Table 2.8 provides the average deviation (cm) between daily cumulative observed and predicted drain flow and runoff averaged over the four replications, for each of the eight years for each of the seven K_{sat} methods, along with the total average deviation over all eight years. The smallest deviation in cumulative outflows for each year is underlined. Similar to the daily deviation results (Table 2.7), there is no one method that provides the smallest deviation in cumulative drain flow and runoff in each year. However, when we consider the total cumulative deviation over all eight years, the van Schilfgaarde equation estimated K_{sat} simulations again produced the smallest total deviation in both drain flow and runoff.

Figures 2.8 through 2.11 are the cumulative drain flow and runoff for two of the individual replicates in 1971 using the van Schilfgaarde equation estimated K_{sat} values (Figures 2.8 and 2.9) and MUUF Soil Database K_{sat} values (Figures 2.10 and 2.11). These figures illustrate again the differences in predictions between these two K_{sat} estimation methods, and how the cumulative flows correspond to the event-based data shown in Figures 2.4 through 2.7. What is important to note in Figures 2.8 through 2.11 is how much better the predicted cumulative flows using the van Schilfgaarde equation estimated K_{sat} values were compared to the MUUF Database values. The average differences between the total cumulative drain flow and runoff for the van Schilfgaarde equation based K_{sat} simulation are 1.7 and 0.8 cm (0.7 and 0.3 in), respectively. The average differences for MUUF Soil Database based K_{sat} simulations are 4.3 and 1.8 cm (1.7 and 0.7 in) for drain flow and runoff, respectively.

Table 2.9 provides a summary of the annual total of precipitation and irrigation, and average total cumulative drain flow and runoff for the eight simulation years for April 1-September 31 (183 days). Also included in Table 2.9 are the measured and predicted average total cumulative and the differences. For the drain flow data, the simulations underpredicted

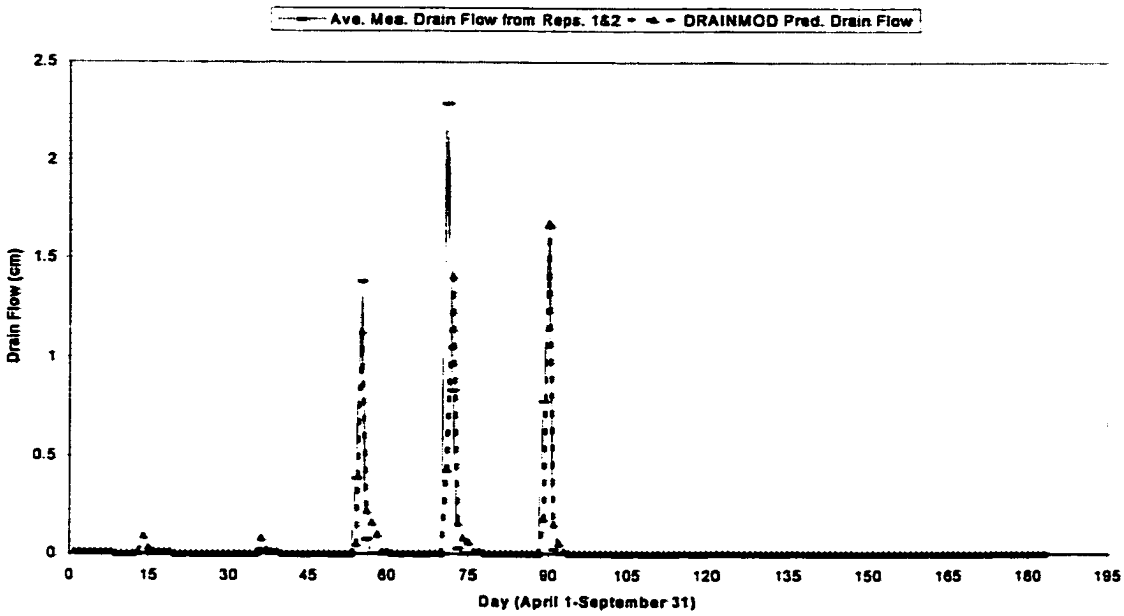

Figure 2.4. Daily predicted (using van Schilfgaarde equation estimated K_{sat}) and average measured drain flows from replications of 1 and 2 during 1971 at the drainage experiment of OARDC North Central Branch, near Sandusky, Ohio (Schwab et al., 1963; 1975; and 1985).

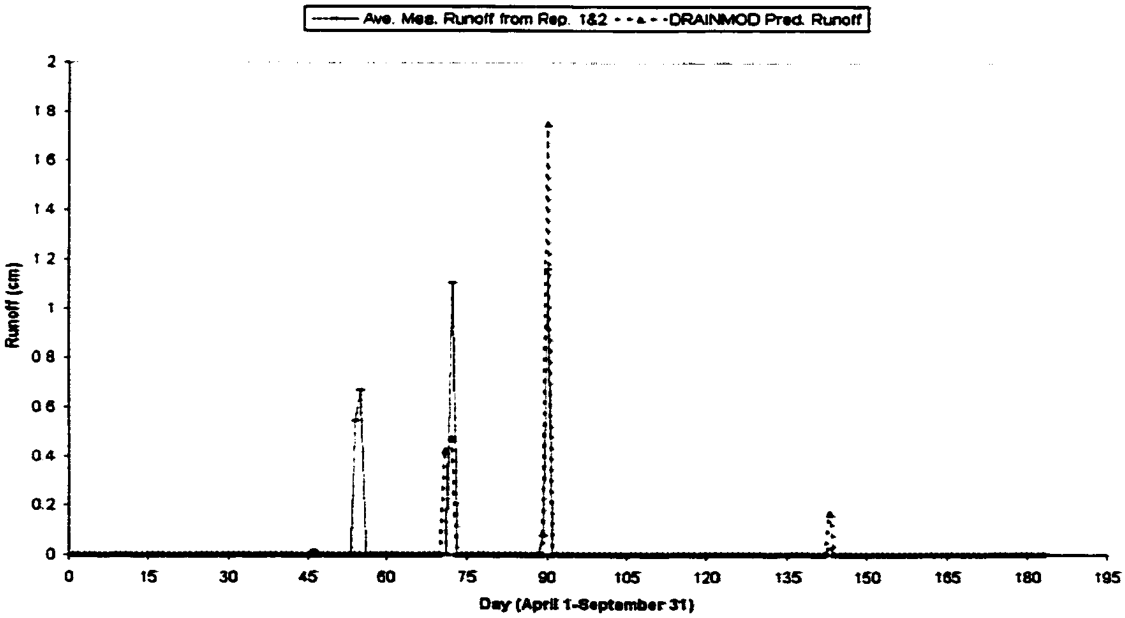

Figure 2.5. Daily predicted (using van Schilfgaarde equation estimated K_{sat}) and average measured runoff from replications of 1 and 2 during 1971 at the drainage experiment of OARDC North Central Branch, near Sandusky, Ohio (Schwab et al., 1963; 1975; and 1985).

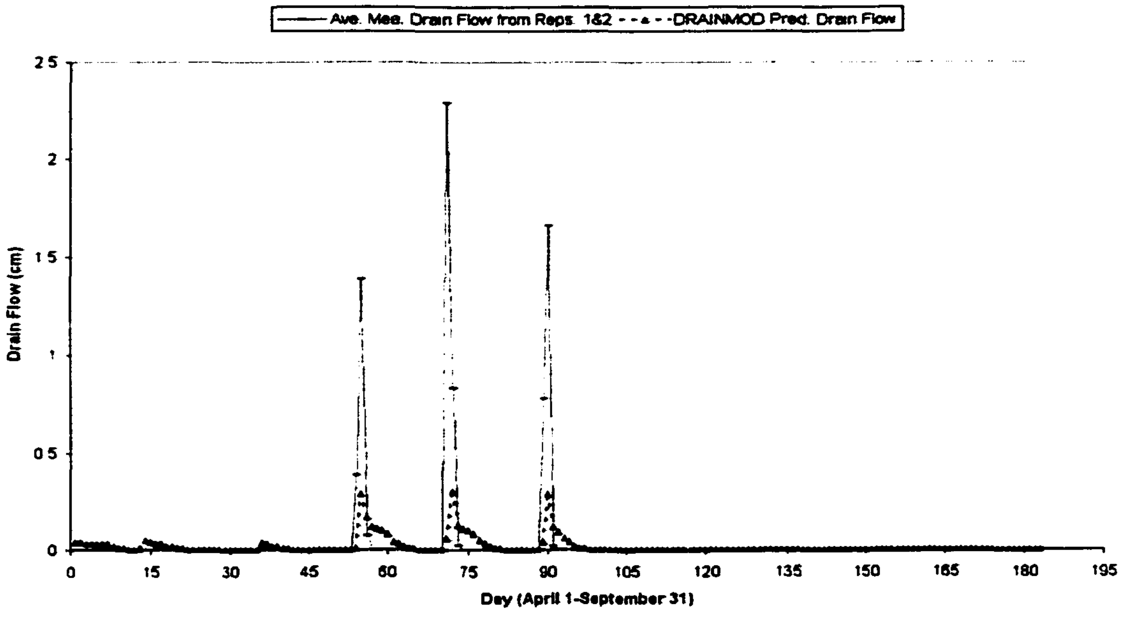

Figure 2.6. Daily predicted (using MUUF Soil Database estimated K_{sat}) and average measured drain flows from the replications of 1 and 2 during 1971 at the drainage experiment of OARDC North Central Branch, near Sandusky, Ohio (Schwab et al., 1963; 1975; and 1985).

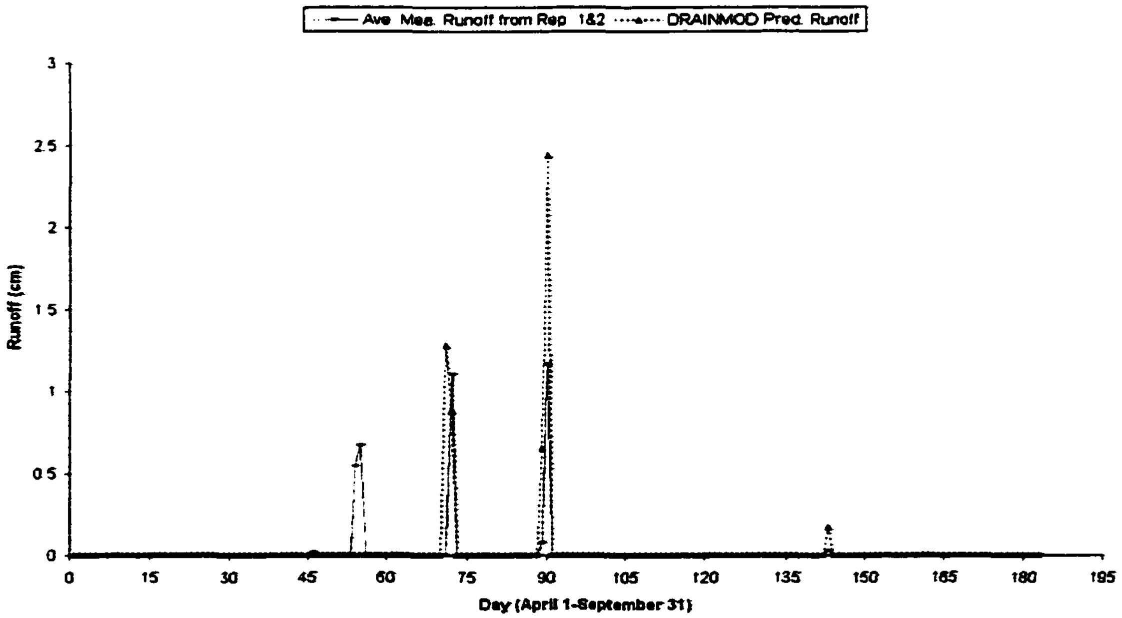

Figure 2.7. Daily predicted (using with MUUF Soil Database estimated K_{sat}) and average measured runoff from the replications of 1 and 2 during 1971 at the drainage experiment of OARDC North Central Branch, near Sandusky, Ohio (Schwab et al., 1963; 1975; and 1985).

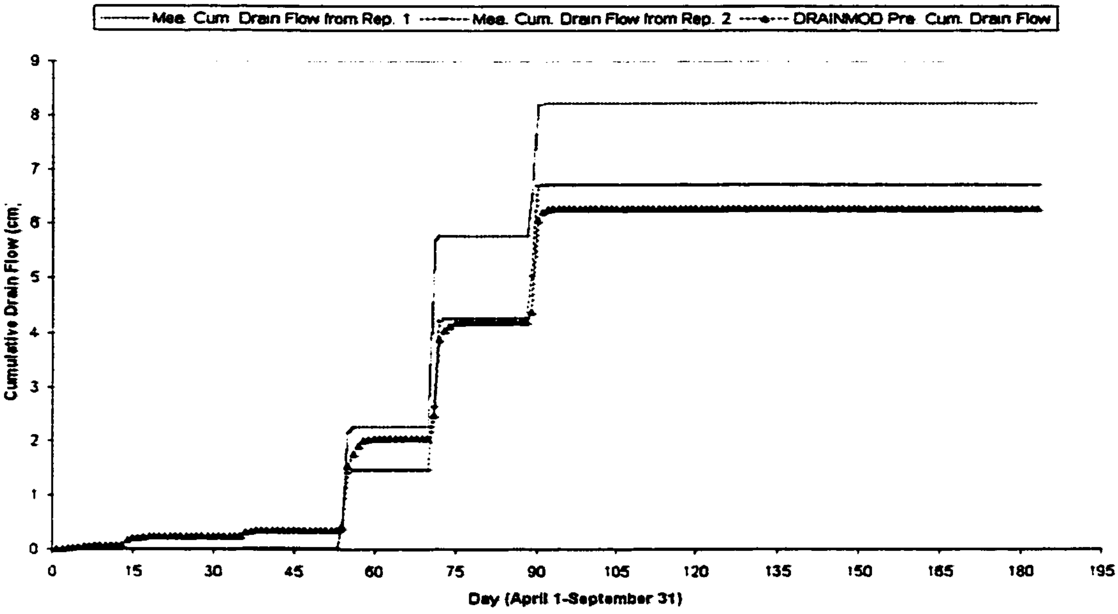

Figure 2.8. Predicted (using van Schilfgaarde equation estimated K_{sat}) and measured cumulative drain flows from replications 1 and 2 during 1971 at the drainage experiment of OARDC North Central Branch (Schwab et al., 1963; 1975; and 1985).

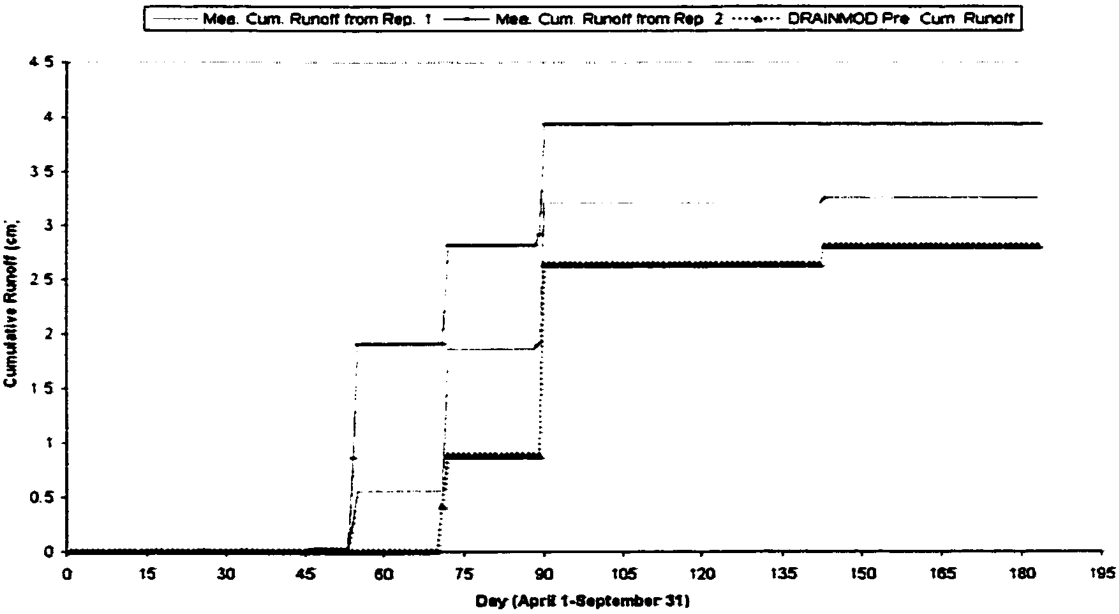

Figure 2.9. Predicted (using van Schilfgaarde equation estimated K_{sat}) and measured cumulative runoff from replications 1 and 2 during 1971 at the drainage experiment of OARDC North Central Branch (Schwab et al., 1963; 1975; and 1985).

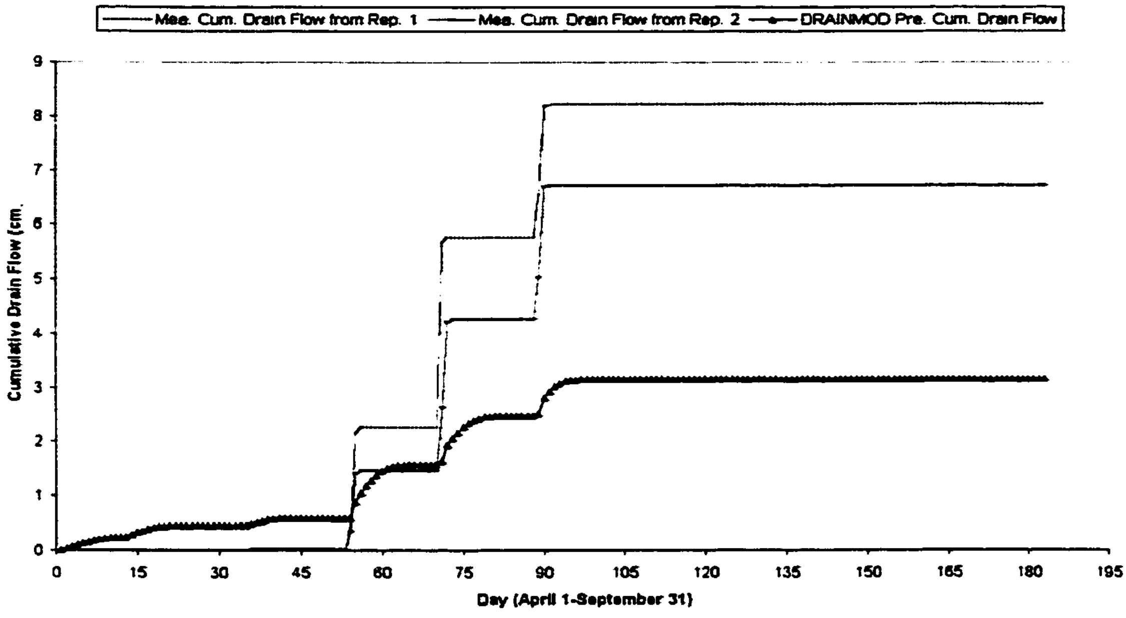

Figure 2.10. Predicted (using with MUUF Soil Database estimated K_{sat}) and measured cumulative drain flow from the replications 1 and 2 during 1971 at the drainage experiment of OARDC North Central Branch, near Sandusky, Ohio (Schwab et al., 1963; 1975; and 1985).

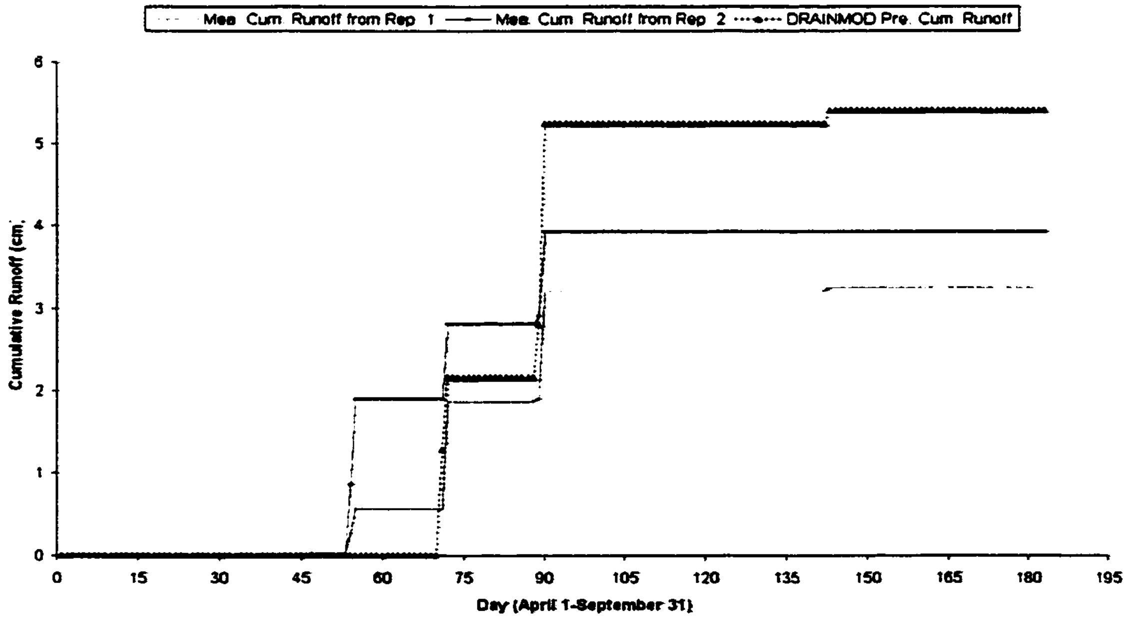

Figure 2.11. Predicted (using with MUUF Soil Database estimated K_{sat}) and measured cumulative runoff from the replications 1 and 2 during 1971 at the drainage experiment of OARDC North Central Branch, near Sandusky, Ohio (Schwab et al., 1963; 1975; and 1985).

		Drain Flow (cm)			Runoff (cm)		
Year	Rainfall*	Measured	Predicted	Difference+	Measured	Predicted	Difference
1962	57.01	8.89	6.06	-2.83	2.25	3.07	+0.82
1963	40.24	12.28	4.41	-7.87	1.64	1.68	+0.04
1964	59.71	20.21	14.79	-5.42	3.28	2.36	-0.92
1967	56.90	9.76	14.12	+4.36	6.57	3.72	-2.85
1968	57.47	9.65	9.00	-0.65	7.92	3.97	-3.95
1969	86.62	19.30	22.83	+3.53	25.64	26.36	+0.72
1970	67.62	12.50	14.56	+2.06	13.46	5.41	-8.05
1971	55.20	6.35	6.31	-0.04	5.25	2.88	-2.37
Total	480.77	98.94	92.08	-6.86	66.01	49.45	-16.56

*: Includes both total rainfall and irrigation (cm) for the months of April through September of each year.

+: Predicted minus measured.

Table 2.9. Predicted outflows (using with van Schilfgaarde equation based K_{sat}) with the average measured values from the drainage experiment station of OARDC North Central Branch, near Sandusky, Ohio.

about half the time (also see Figure 2.12), and a net difference over the eight years (total of rainfall and irrigation was 480.77 cm, 189.3 in) of 6.86 cm (2.70 in). The runoff was also underpredicted in five of the eight years (Figure 2.13) with a net difference of 16.56 cm (6.52 in). The results of a similar analysis for the other five K_{sat} methods (Appendix H, Table H.3 and H.4) produced larger total net average differences in drain flow and runoff than for the van Schilfgaarde equation estimated K_{sat} simulations, except for the Hooghoudt equation estimated K_{sat} simulations.

While the goal of this modeling work was to identify the K_{sat} estimation method that produced the smallest daily and cumulative deviations, accurate prediction of total flow is also important. When the average total difference between predicted and measured drain flows is considered, the minimum absolute difference value for drain flow (Table H.3) was obtained from the Kirkham equation estimated K_{sat} simulations. The rank order (smallest to largest total absolute difference) of the K_{sat} methods for drain flow was the Kirkham equation estimated K_{sat}

Figure 2.12. Predicted (using van Schilfgaarde eq. based K_{sat}) and measured total cumulative drain flows (183 days) at the drainage experiment of OARDC North Central Branch, near Sandusky, Ohio (Schwab et al., 1963; 1975; and 1985).

Figure 2.13. Predicted (using van Schilfgaarde eq. based K_{sat}) and measured total cumulative runoff (183 days) at the drainage experiment of OARDC North Central Branch, near Sandusky, Ohio (Schwab et al., 1963; 1975; and 1985).

method, followed by the auger hole, Hooghoudt, van Schilfgaarde, MUUF, core, and monolith methods. When the average total absolute difference for runoff is considered, the minimum absolute difference value for runoff (Table H.4) was obtained from the MUUF soil database estimated K_{sat} simulations. The subsequent rank order (smallest to largest total absolute difference) of the remaining six K_{sat} methods for runoff was core, monolith, van Schilfgaarde, Hooghoudt, auger hole, and Kirkham equation.

From this point forward, the research incorporates the results of the K_{sat} evaluations, and model simulations use the K_{sat} values obtained with the van Schilfgaarde equation.

2.4.2 Hydraulic Conductivity Changes In Backfill

The predicted and measured average drainage and runoff outflows for the eight years of the field study are illustrated in Figures 2.12 and 2.13. In general, until 1967 the predicted drain flows were less than the measured drain flows. Beginning in 1967, the situation reverses itself. The predicted runoff was less than the measured runoff for all years except 1962 and 1969.

Starting with 1962 (3 years after drainage system installation and in which drain flow and runoff measurements started), Equation 2.15 was applied to the van Schilfgaarde equation estimated K_{sat} values for the years 1963, 1964, 1967, 1968, 1969, 1970, and 1971 (4, 5, 8, 9, 10, 11, and 12 years after drain installation). As mentioned before, the van Schilfgaarde equation estimated K_{sat} values were based on field measured drain flows and water table depths from the same site for the years 1960, 1961, and 1962. Assuming that these estimated K_{sat} values were valid for 1962, adjusted K_{sat} values for the rest of the test years were then obtained by taking the ratio of the predicted maximum drain flow calculated by Equation 2.15 to the maximum drain flow obtained again using Equation 2.15 for the year of 1962. Then the van Schilfgaarde equation estimated K_{sat} values previously given in Table 2.4 were multiplied by the ratios given in Table 2.10 with the resulting adjusted K_{sat} values shown in Table 2.11.

Using the adjusted K_{sat} values in Table 2.11, the simulations were conducted again, and deviations between measured and predicted outflow were calculated as given in Table 2.12. The average deviations obtained by the previous analyses (Table 2.7) using van Schilfgaarde equation estimated K_{sat} values are given in Table 2.12 to illustrate the improvement in model predictions when K_{sat} values decreased over time (note the first two column pairs when PET adjustment is a constant value of 1.0). Note that no adjustment in K_{sat} was made for the 1962 simulations. Except for the 1963 and 1964 simulations, the use of the adjusted K_{sat} values improved model predictions (decreased average deviation). In 1963, there was no change. In 1964, there was an

Year	Years after Installation of Drains	Maximum Drain Flow (m^3/day)	Maximum Drain Flow Ratio
1962	3	0.221	1.000
1963	4	0.189	0.856
1964	5	0.168	0.759
1967	8	0.130	0.589
1968	9	0.122	0.553
1969	10	0.115	0.523
1970	11	0.110	0.496
1971	12	0.105	0.474

Table 2.10. Maximum drain flows using Equation 2.15 and the ratios of maximum drain flows used to calculate adjusted K_{sat} values for Toledo silty clay to account for decreased conductivity with time in the backfill material.

Layer Depth	Years							
(cm)	1962	1963	1964	1967	1968	1969	1970	1971
0-20	42.477	36.377	32.255	25.038	23.498	22.201	21.090	20.123
20-50	1.920	1.644	1.458	1.132	1.062	1.003	0.953	0.910
50-102	0.052	0.044	0.039	0.031	0.029	0.027	0.026	0.025
102-105	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010

Table 2.11. Adjusted van Schilfgaarde equation based K_{sat} values (cm/hr) for Toledo silty clay assuming backfill hydraulic conductivity values decrease with time after installation of drains.

increase in average deviation for drain flow and runoff possibly resulting from a number of factors. For instance, the data of Taylor and Fausey (1982) show a decrease in maximum peak flow within one year of installation. However, while their data and the data of Schwab et al. (1963; 1975; and 1985) were for the same soil at the same site, the drainage pipe installation method, trench width and depth, and drain depth and spacing were not the same. When the total average deviations were summed over all eight years of simulation, the adjusted K_{sat} values produced a decrease in total average deviation in drain flow, but produced an increase in total average deviation in runoff. The increase in runoff deviation resulted from the runoff deviation

	Constant K_{sat}/Constant PET		Adjusted K_{sat}/Constant PET		Constant K_{sat}/Adjusted PET		Adjusted K_{sat}/Adjusted PET	
Year	Drain flow	Runoff	Drain flow	Runoff	Drain flow	Runoff	Drain flow	Runoff
1962	0.048	0.012	0.048	0.012	0.048	0.011	0.048	0.011
1963	0.044	0.007	0.044	0.007	0.052	0.007	0.053	0.007
1964	0.069	0.010	0.074	0.015	0.078	0.011	0.081	0.010
1967	0.039	0.027	0.035	0.026	0.027	0.027	0.026	0.026
1968	0.034	0.030	0.029	0.029	0.030	0.035	0.029	0.034
1969	0.043	0.032	0.042	0.037	0.042	0.034	0.042	0.038
1970	0.055	0.047	0.051	0.045	0.048	0.049	0.045	0.046
1971	0.024	0.020	0.022	0.019	0.028	0.024	0.029	0.024
Total	0.356	0.185	0.345	0.190	0.353	0.198	0.353	0.196
Total Outflow	0.541		0.535		0.551		0.549	

Table 2.12. Average deviations (cm) between daily observed and predicted outflows using constant and adjusted van Schilfgaarde equation estimated K_{sat} values with PET adjustment factors with a constant value of 1.0 (left half of this table) and with PET adjustment factors from Table 2.11 (right half of this table).

increase for only two individual years, 1964 and 1967. Overall, however, the total outflow deviations (Table 2.12) decrease with the use of the adjusted K_{sat} values.

As noted from the data in Table 2.12, deviations in drain flow in 1967 decreased with the use of the adjusted K_{sat} values while deviations in runoff increased. These results are further illustrated in Figures 2.14 through 2.17 where simulation predictions are compared to the average of two of the replicates. The peak flows in Figure 2.15 (adjusted K_{sat}) for individual events show slight decrease when compared to the same events in Figure 2.14. However, peak runoff using the adjusted K_{sat} values shown in Figure 2.17 are generally larger than those in Figure 2.16. The use of adjusted (decreasing) K_{sat} values may have helped increase runoff for selected events in 1967, as well as 1964.

2.4.3 Monthly PET Adjustment Factors

Estimated monthly PET values using the Thornthwaite and Penman-Monteith methods and the subsequent PET adjustment factors are given in Table 2.13 for April through September for each year of this study. As expected, the Thornthwaite method PET values are generally less than those using the Penman-Monteith method for the spring months and generally larger for the summer months. The PET adjustment factors shown in Table 2.13 are the ratios of the estimated monthly PET calculated by Penman-Monteith to those from Thornthwaite. The obtained monthly PET adjustment factors show a similar trend to those obtained by Fouss et al. (1987) for Louisiana conditions, except that the Ohio factors are slightly larger which may result from climatic differences.

The effect of PET adjustment factors on drain flow and runoff predictions was evaluated for all eight years of observed data using both the constant and adjusted van Schilfgaarde equation estimated K_{sat} values. The calculated average deviations between daily observed and predicted outflows are also given in Table 2.12, and the average deviations between cumulative observed and predicted outflows were also calculated. Based on the results in Table 2.12 using the non-constant PET adjustment factors compared to using constant K_{sat} and PET adjustment factors, there is no consistent trend in prediction improvement. For each individual year, except 1967 and 1970, deviations generally remained the same or increased. The use of the non-constant PET adjustment factors for 1967 improved prediction accuracy of the model for both drain flow and runoff. Prediction accuracy for 1970 was improved except for runoff deviations when using the constant K_{sat} values. Observed drain flows in April and May of these two years (1967, 1970)

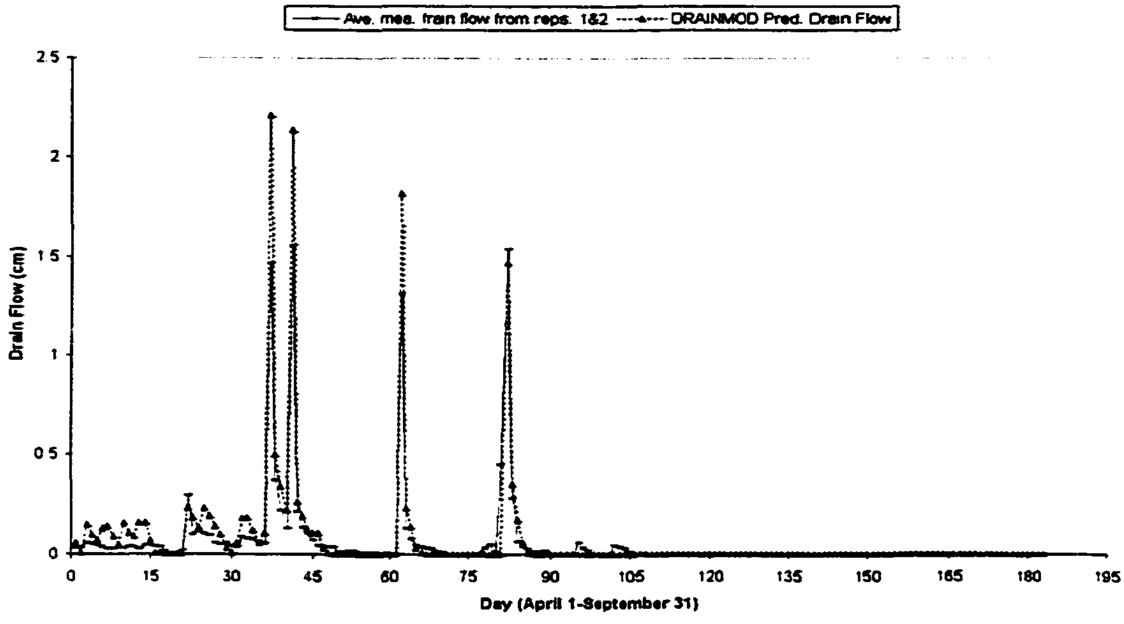

Figure 2.14. Predicted (using constant van Schilfgaarde equation estimated K_{sat}) and average measured daily drain flows from replications 1 and 2 during 1967 for the Toledo silty clay soil at the OARDC North Central Branch, near Sandusky, Ohio.

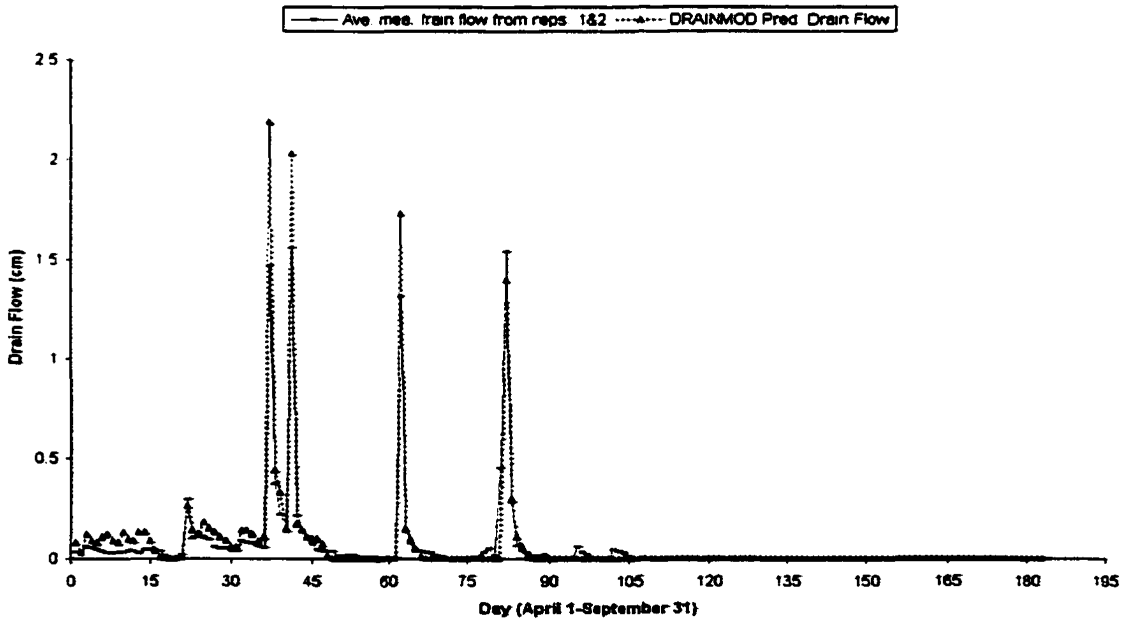

Figure 2.15. Predicted (using adjusted van Schilfgaarde equation estimated K_{sat}) and average measured daily drain flows from replications 1 and 2 during 1967 for the Toledo silty clay soil at the OARDC North Central Branch, near Sandusky, Ohio.

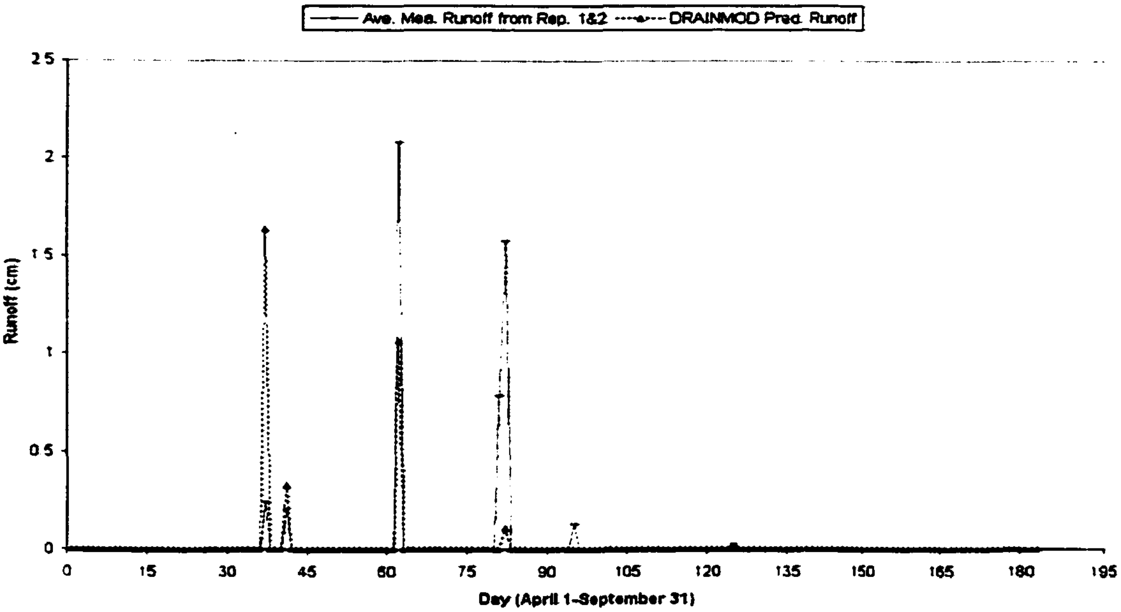

Figure 2.16. Predicted (using constant van Schilfgaarde equation estimated K_{sat}) and average measured daily runoff from replications 1 and 2 during 1967 for the Toledo silty clay soil at the OARDC North Central Branch, near Sandusky, Ohio.

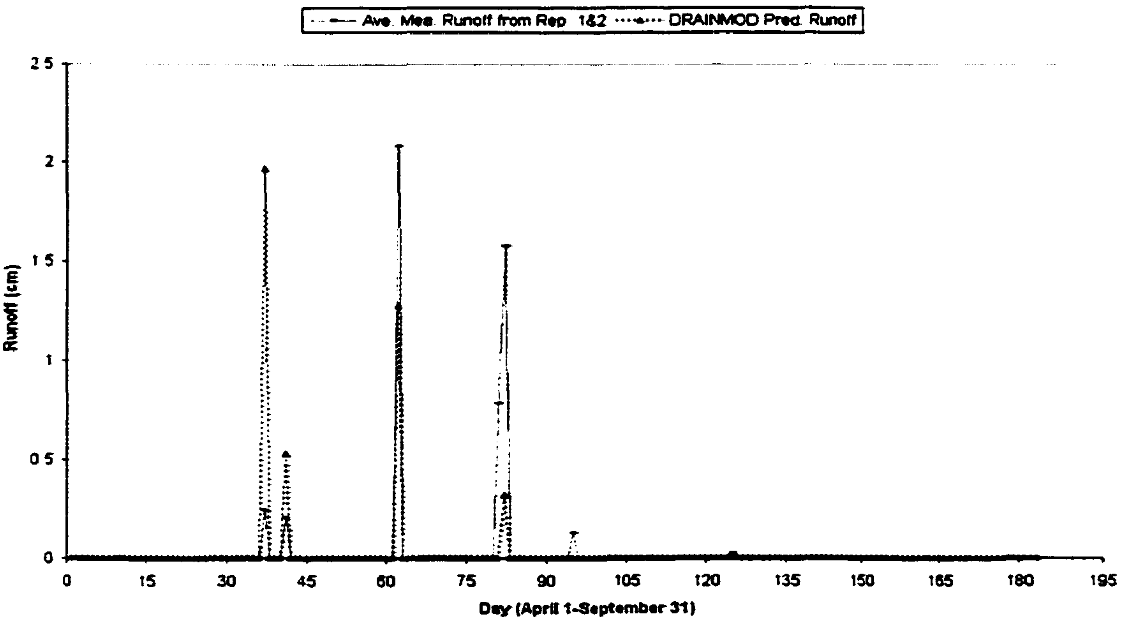

Figure 2.17. Predicted (using adjusted van Schilfgaarde equation estimated K_{sat}) and average measured daily runoff from replications 1 and 2 during 1967 for the Toledo silty clay soil at the OARDC North Central Branch, near Sandusky, Ohio.

Year	Method	Months					
		April	May	June	July	August	September
1962	Penman-Monteith	10.44	13.35	12.88	11.57	11.47	8.45
	Thornthwaite	5.15	11.57	13.31	13.91	12.98	8.55
	PET factor	2.03	1.15	0.97	0.83	0.88	0.99
1963	Penman-Monteith	9.28	11.56	12.91	14.22	10.76	8.64
	Thornthwaite	4.82	8.32	13.12	15.13	12.31	8.42
	PET factor	1.92	1.39	0.98	0.94	0.87	1.03
1964	Penman-Monteith	8.51	14.57	14.48	14.56	11.93	9.98
	Thornthwaite	4.53	10.18	12.88	15.66	12.18	9.37
	PET factor	1.88	1.43	1.12	0.93	0.98	1.06
1967	Penman-Monteith	9.34	11.58	14.50	12.48	10.17	8.38
	Thornthwaite	4.75	6.66	14.03	13.23	12.01	7.21
	PET factor	1.97	1.74	1.03	0.94	0.85	1.16
1968	Penman-Monteith	10.48	9.73	12.41	12.83	11.26	7.99
	Thornthwaite	5.17	7.26	12.51	14.38	13.74	9.67
	PET factor	2.03	1.34	0.99	0.89	0.82	0.83
1969	Penman-Monteith	8.76	11.28	10.47	10.87	12.85	8.13
	Thornthwaite	3.88	7.62	10.57	13.65	12.69	8.58
	PET factor	2.26	1.48	1.00	0.80	1.01	0.94
1970	Penman-Monteith	7.89	12.30	12.65	12.02	11.63	8.80
	Thornthwaite	4.45	9.71	12.07	14.05	12.27	9.19
	PET factor	1.77	1.27	1.05	0.86	0.95	0.96
1971	Penman-Monteith	9.63	12.44	13.55	13.64	13.00	8.23
	Thornthwaite	3.49	7.65	13.59	13.27	11.54	9.61
	PET factor	2.76	1.63	1.00	1.03	1.13	0.86
Average monthly PET factor		2.08	1.43	1.02	0.90	0.94	0.98
Variance		0.10	0.04	0.00	0.00	0.01	0.01
Standard Deviation		0.31	0.19	0.05	0.07	0.10	0.11

Table 2.13. Predicted monthly PET values (cm) using the Thornthwaite and Penman-Monteith methods and the calculated monthly PET adjustment factors obtained using temperature data from the OARDC North Central Branch Station and all other weather data from Toledo, Ohio.

were much larger than in all other years, and these large drain flows with the PET adjustment factors produced better outflow prediction accuracy. Considering the total daily average deviation in drain flow and runoff given in Table 2.12, drain flow deviations decreased while runoff deviations increased. When we consider the overall total outflow, using the non-constant PET monthly adjustment factors decreased the prediction accuracy of the model.

The general lack of prediction improvement using the calculated PET adjustment factors can be further illustrated by comparing the outflow data in Figures 2.18 and 2.19 with the data shown previously in Figures 2.4 and 2.5 (using a PET adjustment factor of 1.0 for all months). Simulations shown in Figures 2.18 and 2.19 appear to predict no drain flow or runoff for events at day 50 and 70, and the only change is the use of the PET adjustments. For April and May, the adjustment values are 2.76 and 1.63, respectively. When the PET factor is larger than 1.0, the soil water available for drain flow is being used as more evapotranspiration. Based on the above results, the use of calculated PET adjustment factors may not be warranted for the work that follows in this study since model prediction accuracy was not generally improved. Therefore all further model analyses will be conducted using a value of 1.0 for the monthly PET adjustment factor. This combination with the Thornthwaite PET estimates provides reasonable daily drain flow and runoff predictions.

2.4.4 Evaluation of Kirkham-Hooghoudt Equations on Drain Flow and Runoff Prediction Using DRAINMOD

After considering the possible effects on hydraulic conductivity of consolidation of the trench backfill, comparisons between Equation 2.12 and the Kirkham-Hooghoudt equations were made for the years 1962, 1963, and 1964. Equation 2.12 (Hoffman, 1963) was developed using midspace water table elevation and the corresponding drain flow data for the years 1960 through 1962. As previously stated the Kirkham-Hooghoudt equations for these years underpredicted drain flow (Fig. 2.12) and closely predicted runoff (Fig. 2.13). Remember that the results presented in Figures 2.12 and 2.13 were produced with the van Schilfgaarde equation estimated K_{sat} values. Based on the above results, however, it may not be appropriate to say that the Kirkham-Hooghoudt equations as used in DRAINMOD (Version 4.6) consistently underpredict drain flows, mainly because of the use of a drainage coefficient, DC. In the current research, a DC value of 5.3 cm/day (2.1 in/day) was used, which restricted the drain flows predicted by the Kirkham-Hooghoudt equations when the water table depth was less than 1.8 cm (0.7 in). Therefore, the drain flow prediction capacity of Kirkham-Hooghoudt solution was not

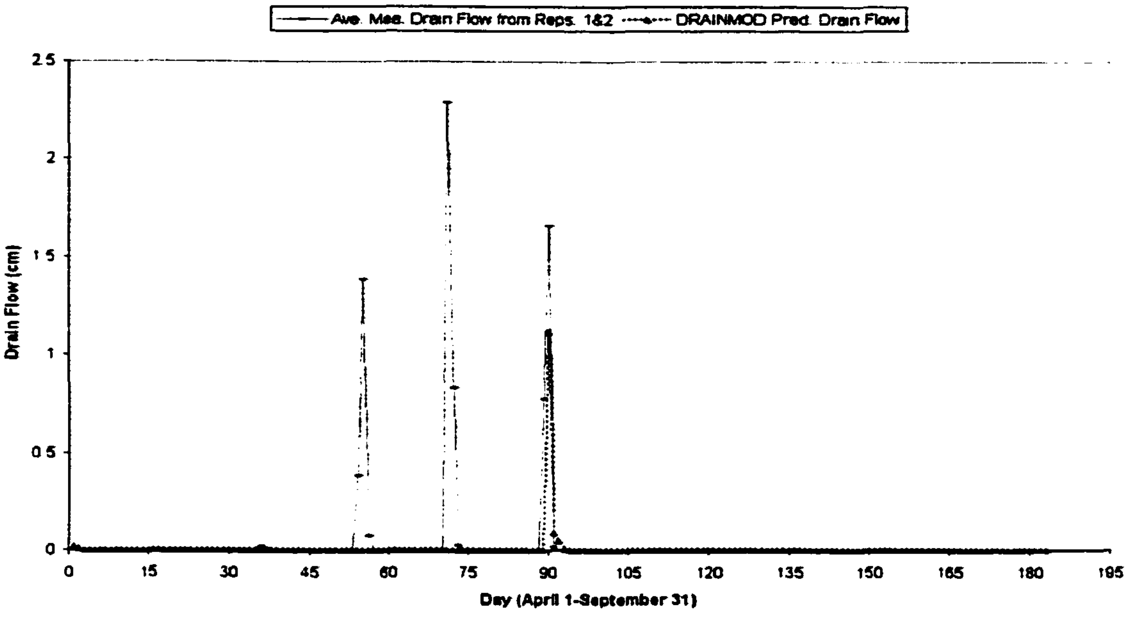

Figure 2.18. Predicted (using adjusted van Schilfgaarde equation estimated K_{sat} and monthly PET factors) and average measured daily drain flows from replications 1 and 2 during 1971 at the drainage experiment of OARDC North Central Branch (Schwab et al., 1963; 1975; and 1985).

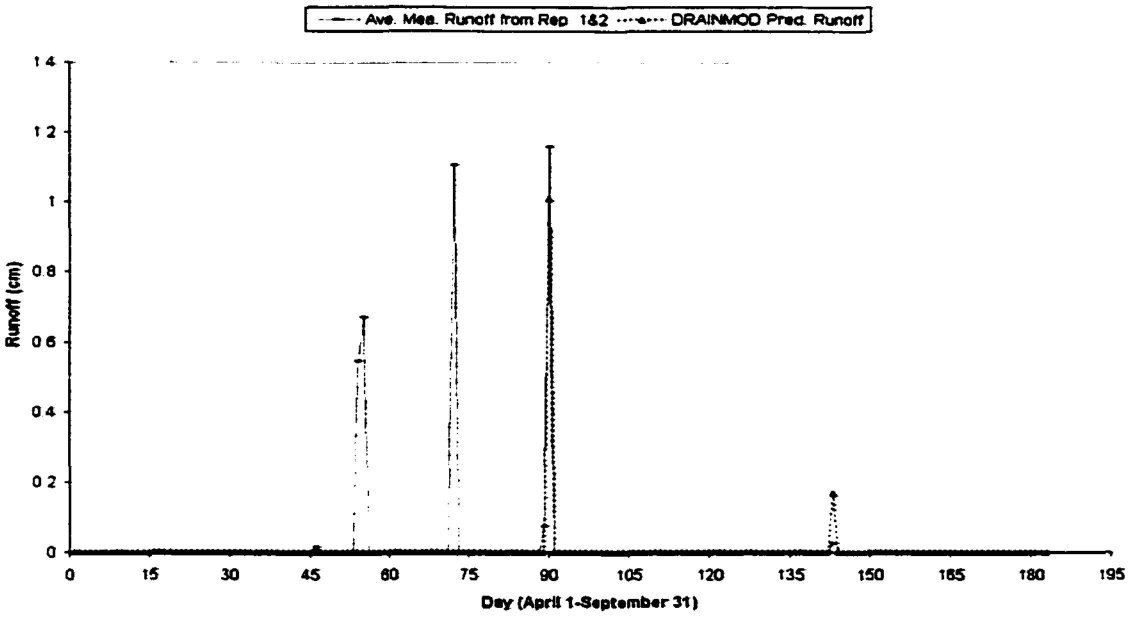

Figure 2.19. Predicted (using adjusted van Schilfgaarde equation estimated K_{sat} and monthly PET factors) and average measured daily runoff from replications 1 and 2 during 1971 at the drainage experiment of OARDC North Central Branch (Schwab et al., 1963; 1975; and 1985).

completely used in these simulations because of the lateral drain pipe capacity (DC). However, we do not know how many times the model met with this kind of situation for the years 1962, 1963, and 1964.

If the water table is assumed to be (1.8 cm depth) very close to the soil surface and effects of this depth increment on drain flow can be neglected, the accuracy of the Kirkham-Hooghoudt equations can be evaluated using Equation 2.12 in place of the Kirkham and Hooghoudt equations, along with the same input data. As mentioned before, a DC value of 5.3 cm/day (2.1 in/day) was obtained using Equation 2.12, and this value is the maximum drain flow rate when the water table is at the soil surface (i.e., water table elevation above centerline of the drain of 90 cm = 35.4 in). Therefore, when DRAINMOD is used with Equation 2.12 and DC = 5.3 cm/day, the maximum drain flow predicted by DRAINMOD will not be limited by DC parameter.

The calculated average deviations between Equation 2.12 simulation predicted outflows and the measured outflows for 1962 through 1964 are given in Table 2.14, along with the previous results obtained from the Kirkham-Hooghoudt simulations (Appendix H, Tables H.1 and H.2) for the same years. The minimum deviations for each year and replication for drain flow and runoff are underlined. Based on the results in Table 2.14 using Equation 2.12, drain flow deviations were generally reduced compared to those using the Kirkham-Hooghoudt equations, but this trend was reversed for runoff. Considering the daily average deviations in drain flow and runoff, drain flow deviations decreased for 1963 and 1964 and runoff deviations decreased for 1962 and 1963 using Equation 2.12. When we consider the cumulative average deviations shown in Table 2.14, drain flow average deviations decreased for all three years, and runoff average deviations decreased for 1962 but increased for 1963 and 1964. When we compare the total of the average deviations (bottom of table) for daily and cumulative obtained using Equation 2.12 with those obtained using the Kirkham-Hooghoudt equations overall three years, Equation 2.12 gave smaller deviation values for drain flow, and larger deviations for runoff.

Simulated seasonal (183 days) drain flow and runoff depths are shown in Figures 2.20 and 2.21, respectively, for these three years. While both equations (using DC = 5.3 cm/day) underpredicted seasonal drain flow depth (Fig. 2.20), Equation 2.12 predicted seasonal drain flows that were 32.5, 22.4, and 14.1% greater than those using the Kirkham-Hooghoudt equations, and improved seasonal drain flow predictions by 22.1, 8.1, and 12.0% for 1962, 1963, and 1964, respectively. For runoff (Fig. 2.21), the Kirkham-Hooghoudt equations overpredicted

		Equation 2,12 Simulations				Kirkham-Hooghoudt Simulations			
		Daily Average Deviation (cm)		Cumulative Average Deviation (cm)		Daily Average Deviation* (cm)		Cumulative Average Deviation+ (cm)	
Year	Replications	Drain Flow	Runoff	Drain Flow	Runoff	Drain Flow	Runoff	Drain Flow	Runoff
1962	1	0.0296	0.0072	0.988	0,311	0,0311	0,0084	1,941	0.078
	2	0,0255	0.0117	1,054	0.503	0.0202	0,0180	0.638	1,104
	3	0,0900	0.0106	2.389	0.847	0.0821	0,0161	3.701	1,504
	4	0,0662	0,0126	0.603	1,258	0,0576	0.0067	1,773	0.699
	Average	0,0528	0.0105	1.258	0.730	0.0480	0,0120	2,013	0,846
1963	1	0.0531	0,0036	5.983	0.371	0,0570	0.0023	6,454	0.090
	2	0.0272	0,0093	2.377	0.985	0,0274	0.0079	2.937	0.403
	3	0.0365	0.0043	3.931	0,496	0,0365	0,0073	4,335	0.063
	4	0.0493	0,0096	5.746	0.329	0,0538	0.0091	6,567	0,572
	Average	0.0415	0.0067	4.509	0,545	0,0440	0,0070	5,073	0.282
1964	1	0.0672	0,0135	2.579	1,365	0,0700	0.0121	3.722	1.001
	2	0.0490	0,0143	1.591	1,461	0,0542	0.0129	1,732	1.097
	3	0.0575	0,0147	1.686	1,045	0,0664	0.0143	2,926	0.332
	4	0.0750	0,0087	5.022	0.819	0,0839	0.0019	6,519	0.087
	Average	0.0622	0,0128	2.719	1,172	0,0690	0.0100	3.725	0.626
Total of Averages		0.1565	0,0300	8.486	2,447	0,1610	0.0290	10,811	1.754

*: These data were already given in Table H.1 in Appendix H.
+: These data were already given in Table H.2 in Appendix H.

Table 2,14. Average deviations between daily and cumulative predicted and measured outflows using Equation 2.1 and the Kirkham-Hooghoudt equations. Measured flow data are from (Schwab et al., 1963; 1975; and 1985).

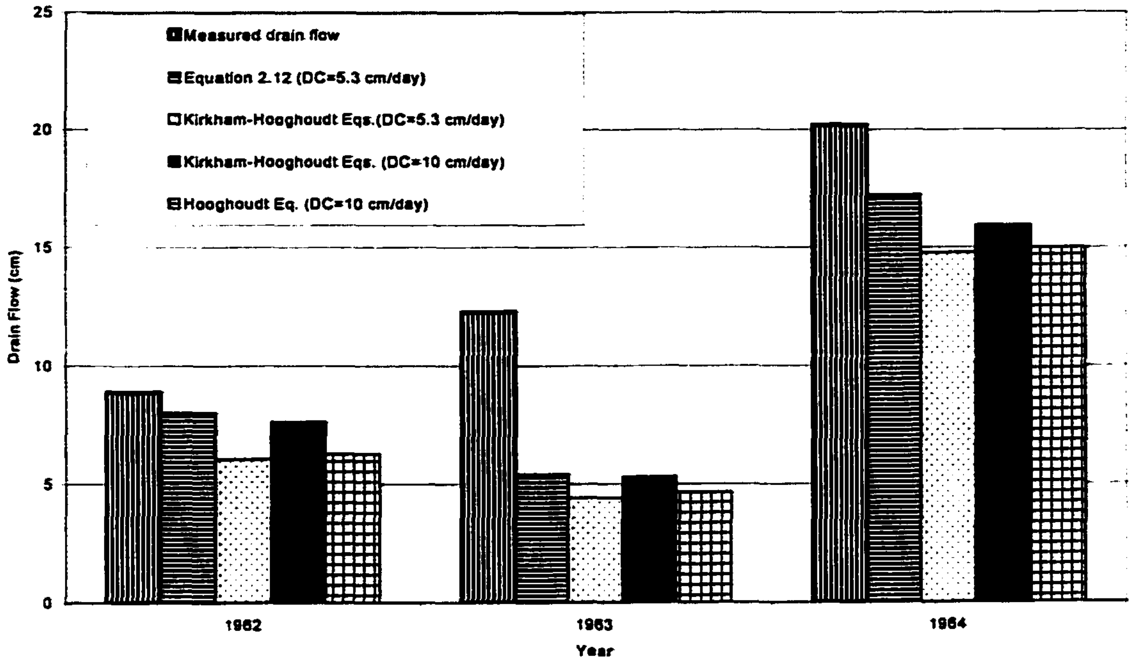

Figure 2.20. Average predicted (using Equation 2.12 with DC=5.3 cm/day, and Kirkham-Hooghoudt equations with DC=5.3 and 10 cm/day) and measured seasonal (183 days) drain flow depths for 1962-1964 (from Schwab et al. 1963; 1975; and 1985).

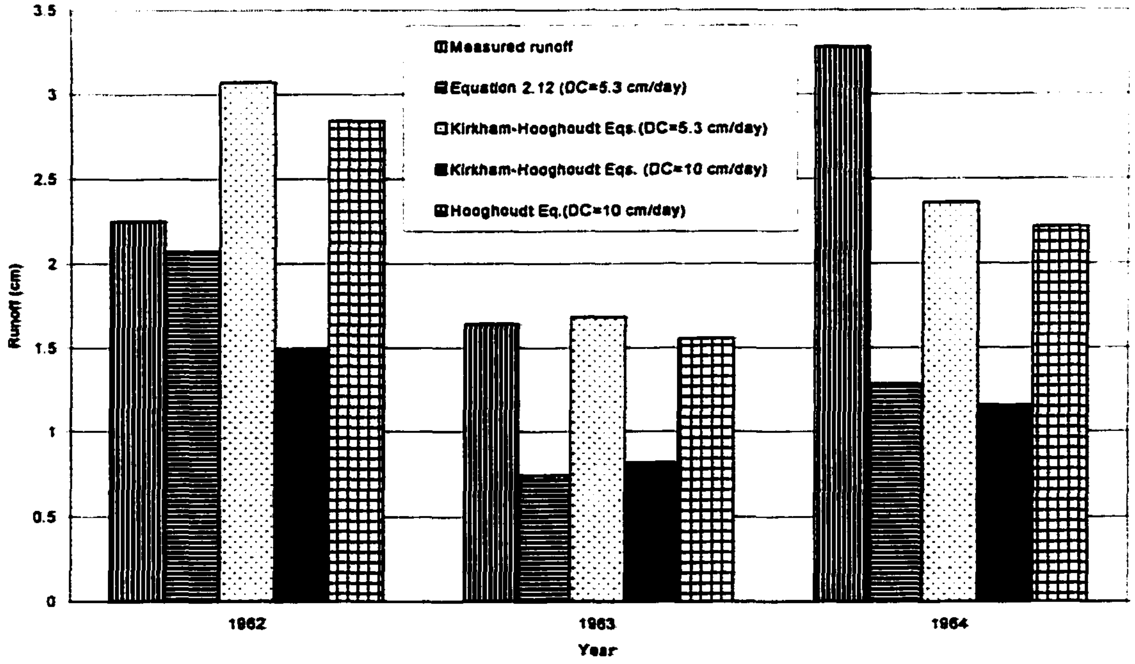

Figure 2.21. Average predicted (using Equation 2.1 with DC=5.3 cm/day, and Kirkham-Hooghoudt equations with DC=5.3 and 10 cm/day) and measured seasonal (183 days) runoff depths for 1962-1964 (from Schwab et al., 1963; 1975; and 1985).

depth in 1962 and 1963, but underpredicted in 1964. Equation 2.12 underpredicted depths in all three years. However, the use of Equation 2.12 improved the prediction by 26% in 1962 over that using the Kirkham-Hooghoudt equations, but worsened the predictions of runoff depth by 43.1 and 32.9% in 1963 and 1964, respectively.

As stated earlier, one possible reason for the underprediction of drain flow depth using the Kirkham-Hooghoudt equations is the drainage coefficient (DC) parameter. The question arises about whether or not the DC produces an apparent capacity limit on model drain flow predictions. To better understand this potential limitation, drain flow predictions with their corresponding midspace water table elevations using both Equation 2.12 and the Kirkham-Hooghoudt equations are illustrated in Figure 2.22. From this figure, it is clear that the Kirkham-Hooghoudt equations do not underpredict drain flow compared to Equation 2.12, but overpredict drain flow for most of the midspace water table elevations at or above 70 cm (27.6 in). Therefore, some part of the underprediction of drain flow for the 1962-1964 seasonal data set presented above may be the result at least in part, of the limitation of the parameter DC.

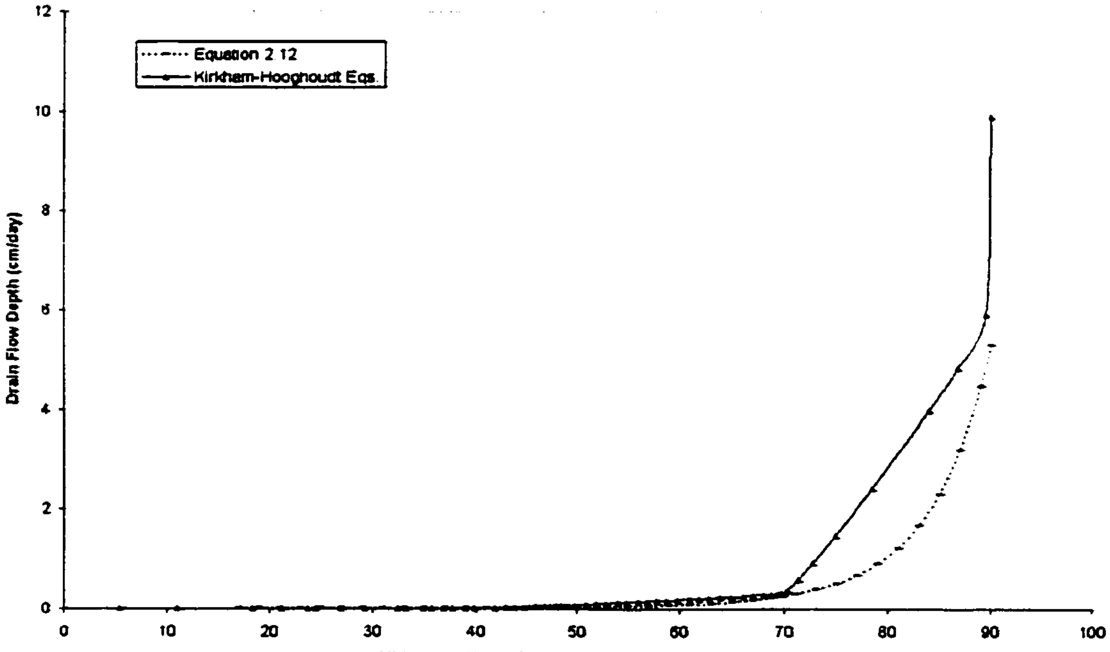

Figure 2.22. Drain flow versus midspace water table elevation obtained using Equation 2.12 and the Kirkham-Hooghoudt equations in DRAINMOD for Toledo silty clay.

To further evaluate the influence of the drainage coefficient on drain flow and runoff, simulations were also conducted with DRAINMOD using a value of DC equal to 10 cm/day (3.9 in/day), which is equal to the maximum drain flow calculated using the Kirkham equation when the water table is at the soil surface. The seasonal outflow depths from this simulation are also shown in Figures 2.20 and 2.21. The simulations using Equation 2.12 (DC=5.3 cm/day) and the Kirkham-Hooghoudt equations (DC=10 cm/day) produced outflows that are now much more in agreement with each other. When the Kirkham-Hooghoudt equations were used with DC=10 cm/day compared to 5.3 cm/day, the depth of predicted seasonal drain flow increased by 26.1, 20.3, and 7.9%, for 1962, 1963, and 1964, respectively, and the Kirkham-Hooghoudt equations seasonal drain flow predictions by 17.8, 7.3, and 5.8%, respectively. However, the predictions from use of the Kirkham-Hooghoudt equations still underpredicted drain flow depth using DC=10 cm/day compared to 5.3 cm/day with the Kirkham-Hooghoudt equations. The predicted seasonal runoff depths decreased by about 51% for all years, and produced depths similar to those using Equation 2.12. The use of DC=10 cm/day improved seasonal runoff prediction in 1962 by 2.5%, but worsened runoff predictions by 47.3 and 36.7%, for 1963 and 1964, respectively.

The above improvement in predicted versus measured drain flow for simulations using a DC value of 10 cm/day (3.9 in/day) compared to 5.3 cm/day (2.1 in/day) is most likely because of the Kirkham component of the Kirkham-Hooghoudt equation combination. To test this, DRAINMOD was run once using the Hooghoudt equation alone with a DC value of 10 cm/day and with the water table at the soil surface. The maximum drain flow was only 5.93 cm/day (2.33 in/day). Then a series of DRAINMOD simulations was run with only the Hooghoudt equation in place of Kirkham-Hooghoudt equations with DC=10 cm/day. The predicted seasonal drain flows and runoff also are shown in Figures 2.20 and 2.21, respectively. Drain flows for all three years with the Hooghoudt equation alone were underpredicted, while runoff was overpredicted for all three years compared to simulations with the Kirkham-Hooghoudt equations. Therefore, using the Hooghoudt equation alone did not improve drain flow prediction. Using the Hooghoudt equation alone, the difference between average predicted and measured drain flows are larger than those obtained with the Kirkham-Hooghoudt equations, with DC=10 cm/day. Thus, the improvement in drain flow predictions using the Kirkham-Hooghoudt equations compared to the Hooghoudt equation alone were 21.6, 14.3, and 6.4% for 1962, 1963, and 1964, respectively.

These increases improved drain flow prediction by 15.2, 5.4, and 4.8%, which is a result of the Kirkham equation. However, with the Hooghoudt equation alone, there is a consistent increase (91% for all three years) in runoff prediction. These increases improved runoff prediction by the Hooghoudt equation alone by 7.7, 45.1, and 32.3% compared to the Kirkham-Hooghoudt equations. In summary, the addition of the Kirkham equation helps increase the drain flow prediction accuracy of DRAINMOD. However, the improvement in drain flows comes at a cost of decreasing runoff prediction accuracy.

2.5 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The overall purpose of this chapter is to present the results of a series of background studies thought to be of interest and necessary towards the improvement of the predictive capability of WEPP. Each of the objectives are listed below with a summary, conclusions, and recommendations relative to each objective. Measured drain flow and runoff data from the drainage experiment at the OARDC North Central Branch station (Schwab et al., 1963; 1975; and 1985) were used in this study. Since DRAINMOD is the most popular model used in USA, the work will be conducted within the frame work of DRAINMOD.

2.5.1 Hydraulic Conductivity Evaluations

The first objective of this study was to evaluate runoff and drain flow predictions from DRAINMOD, using a range of saturated hydraulic conductivity data sets developed for the same site using seven different K_{sat} estimation methods. Simulations using DRAINMOD (Version 4.6) were conducted for the years 1962-1964, and 1967-1971 and predictions were compared to measured outflows from Schwab et al. (1963; 1975; and 1985). The analyses showed that no one K_{sat} estimation method provided the smallest deviation in outflows when individual years were considered, except for drain flow in 1967-1971. For 1967-1971, the simulation results with the van Schilfgaarde equation estimated K_{sat} values produced the smallest average deviation. The van Schilfgaarde equation estimated K_{sat} simulations also produced the smallest deviation in runoff in three of the five years that also had the smallest drain flow deviation. Overall, the simulation results with the van Schilfgaarde equation estimated K_{sat} values produced the smallest total deviation for both drain flow and runoff over all eight test years. The rank order (smallest to largest total deviation) of the K_{sat} methods for drain flow were van Schilfgaarde, Hooghoudt, and Kirkham equations estimated K_{sat} methods, followed by auger hole, monolith, core methods, and then the MUUF soil database method. The rank order of the K_{sat} methods for runoff was van

Schilfgaarde, Hooghoudt, Kirkham, auger hole, MUUF soil database, core, and Monolith. Based on the results of this research, a conclusion was reached to use the van Schilfgaarde equation based K_{sat} in all further analyses in this chapter.

Where drain flow and water table depth measurements are available and/or practical to obtain, K_{sat} estimates made with the van Schilfgaarde equation may provide more reliable modeling results since they take into account the overall effect of backfill, drain spacing and depth, deep percolation, drain pipe parameters, etc.

2.5.2 Hydraulic Conductivity Changes in Backfill

The second objective in this study was to analyse the relative impact of changes in drainage trench backfill properties on runoff and drainage flows. After assuming that hydraulic conductivity decreases in the backfill affected each soil layer's effective hydraulic conductivity, an exponential maximum drain flow equation as a function of year was developed using the maximum drain flow versus year data obtained from the backfill alteration study of Taylor and Fausey (1982). Using this equation, the van Schilfgaarde equation estimated saturated hydraulic conductivity values obtained in previous analysis were adjusted over time. Using these adjusted van Schilfgaarde equation based K_{sat} values in DRAINMOD improved the outflow prediction accuracy of the model.

Determining the changes in hydraulic conductivity of backfill for different subsurface drainage system spacings, depths, trench widths, pipe and backfill material properties is considered a major research need. Developing empirical relations for changes in hydraulic conductivity with time, such as Equation 2.15 may not only improve drain flow prediction capability, but improve the use of models like DRAINMOD for drainage system design and evaluation.

2.5.3 Monthly PET Adjustment Factors

The third objective in this study was to evaluate monthly Potential EvapoTranspiration (PET) adjustment factors used in DRAINMOD to predict drain flow and runoff. To determine the monthly PET adjustment factors for North Central Ohio conditions, the estimated monthly Penman-Monteith PET values were divided by the estimated monthly Thornthwaite PET values. Overall, when DRAINMOD was run with these monthly PET adjustment factors, the outflow prediction accuracy of the model worsened. Therefore, until further study is conducted to better warrant their use, a value of 1.0 for the PET adjustment factors is recommended.

If monthly pan or lake evaporation data are available, these data could be used to determine monthly PET adjustment factors in place of using the Penman-Monteith equation estimated PET values. In general, if the Thornthwaite daily PET estimates are after all proven not to be appropriate, the water balance algorithms in DRAINMOD have to be checked and tested using the daily Penman-Monteith equation or pan evaporation data.

2.5.4 Evaluation of Kirkham-Hooghoudt Equations on Drain Flow and Runoff Prediction Using DRAINMOD

The fourth and last objective in this study was to evaluate the effects of the Kirkham-Hooghoudt equations on drain flow and runoff prediction accuracy of DRAINMOD against an empirical equation, and to determine the relative contribution of the Kirkham equation to drain flow predictions compared to the Hooghoudt equation alone. After assuming that an empirical equation (Eq. 2.12) developed by Hoffman (1963) best describes the water table depth-drain flow relationship expressed by the data at the experimental site, this equation was used in place of the Kirkham and Hooghoudt equations to evaluate the effects of the Kirkham-Hooghoudt equations on drain flow and runoff prediction. Overall, the analyses showed that in comparison to drain flow predictions using Equation 2.12, the Kirkham-Hooghoudt equations did not predict drain flows as well, but did predict runoff better than that with the simulations using Equation 2.12. In addition, careful selection of a value for the drainage coefficient (DC) is necessary when using the Kirkham-Hooghoudt equations since drain flow predicted by the Kirkham and Hooghoudt equations is limited to the value of DC.

The contribution of the Kirkham equation to drain flows was evaluated using DRAINMOD with and without the Kirkham equation; or stated another way, with the Kirkham-Hooghoudt equations and the Hooghoudt equation alone. The analyses showed that the addition of the Kirkham equation to the Hooghoudt equation improved drain flow prediction accuracy of DRAINMOD compared to the Hooghoudt equation alone. However, this capability may decrease the runoff prediction accuracy of the model. Again, careful selection of the DC value is important. Based on these results, the Kirkham equation will be incorporated into the subsurface drainage algorithms of the WEPP-WTM model. To predict drain flow, the WEPP model now only uses the Hooghoudt equation.

After considering the variability of replication-outflow results, when DRAINMOD is used with appropriate input parameters such as K_{sat}, DC, and monthly PET factors, overall drain flow predictions by Kirkham-Hooghoudt solution are good. However, we also have to consider that some years most of the drain flow and runoff depths were a result of the constant intensity irrigation events at the research site. For these irrigation events, the input data for rainfall are equally distributed as hourly constant values. These types of constant intensity storms are not seen often in nature. For this reason, if the rainfall measurement interval is less than an hour, using less than hourly time interval rainfall data, such as breakpoint data usage option in WEPP, may increase the prediction accuracy of the model.

In most of the above simulations using DRAINMOD, when drain flow prediction accuracy improved, runoff prediction accuracy generally worsened. One reason this result may occur is that in all simulations performed in this study, Green-Ampt infiltration parameters determined by Skaggs et al. (1981) were kept constant during the eight year-simulation period. Infiltration rate affects runoff. The values of the Green-Ampt parameters by Skaggs et al. (1981) were based on core method K_{sat} values. Further study is warranted in the selection of Green-Ampt parameter values and the use of various K_{sat} methods for estimating Green-Ampt parameter values. Also, it might be interesting to evaluate the effect of time based adjustments to Green-Ampt parameter values, similar to what was done in this study for backfill effects on K_{sat}.

The author was also interested in developing a new drain flow prediction equation which was planned to be similar to that developed by Salem and Skaggs (1998). The Salem and Skaggs approach was for a homogeneous soil. The work presented in the next chapter focuses on simulating drain flow into subsurface drainage pipe for a layered soil profile with backfill.

2.6 REFERENCES

Allen, R.G. 1994. REF-ET reference evapotranspiration calculation software, Ver. 2.15a. Utah State University Foundation, Utah State Univ., Logan, Utah. 42 p.

Allen, R.G. 1990. REF-ET reference evapotranspiration calculator manual, Ver. 2.0. Utah State University Foundation, Utah State Univ., Logan, Utah. 12 p.

Amatya, D. M., R.W. Skaggs and J.D. Gregory. 1995. Comparison of methods for estimating REF-ET. J. Irrigation and Drainage Engineering, ASCE 121(6):427-435.

Amatya, D. M., R.W. Skaggs and J.D. Gregory. 1992. Comparison of methods for estimating potential evapotranspiration. ASAE Paper No. 92-2630. St. Joseph, Mich.: ASAE. 27 p.

Amoozegar, A. and A.W. Warrick. 1986. Hydraulic conductivity of saturated soils: Field Methods. p:735-768. In A. Klute (Ed.). Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods. SSSA Book Series: 5 (formerly Agronomy Monograph 9). Madison, Wisconsin. 1188 p.

Baumer, Otto W. 1989. Predicting unsaturated hydraulic parameters. p.341:354. In M. Th. van Genuchten and F.J. Leij, and L.J. Lund (Eds.) Proceedings of the international workshop on indirect methods for estimating the hydraulic properties of unsaturated soils. Riverside, California, October 11-13. U.S. Dept. of Agriculture: Dept. of Soil and Environmental Sciences, University of California, c1992. 718 p.

Bouwer, H. and R.D. Jackson. 1974. Determining soil properties, section X. p.611-666. In J. van Schilfgaarde (Ed.). Drainage for Agriculture. Agronomy No. 17. American Society of Agronomy. Madison, Wisconsin. 700 p.

Alexander, C.A. 1988. ADAPT – A model to simulate pesticide movement into drain tiles. Master of Science Thesis. Ohio State University. Columbus, Ohio. 241 p.

Chung, S.O., A.D. Ward and C.W. Schalk. 1992. Evaluation of the hydrologic component of the ADAPT water table management model. Transactions of the ASAE 35(2):571-579.

Dumm, L.D. 1954. Drain spacing formula. Agricultural Engineering 35(10):726-730.

Flanagan, D.C. and S. J. Livingston (Eds). 1995. WEPP user summary. NSERL Report No. 11, USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, Indiana. 131 p.

Flanagan, D.C. and M.A. Nearing (Eds.). 1995. WEPP technical documentation. NSERL Report No. 10, USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, Indiana. 284 p.

Fouss, J.L., R.L. Bengtson and C.E. Carter. 1987. Simulating Subsurface Drainage in the Lower Mississippi Valley with DRAINMOD. Transactions of the ASAE 30(6):1679-1688.

Harrold, L.L. and F.R. Dreibelbis. 1958. Evaluation of agricultural hydrology by monolith lysimeters. Tech. Bull. No. 1179. USDA-Ohio Agricultural Experiment Station. Washington, D.C. 166 p.

Hess, T.M. 1999. Reference Evapotranspiration (Ver. 2)[DAILYET], Cranfield University, Silsoe, UK.

Hoffman, G.J. 1963. Tile flow from a stratified anisotropic soil with a falling water table. Master of Science Thesis. Ohio State University. Columbus, Ohio. 83 p.

Hoffman, G.J. and G.O. Schwab. 1964. Tile spacing prediction based on drain outflow. Transactions of the ASAE 7(4):444-447.

Hooghoudt, S.B. 1940. Algemeene beschouwing van het probleem van de detailontwatering en de infiltratie door middel van parallel loopende drains, greppels, slooteen, en kanalen. Versl. Landbouwk. Onderz. 46(14)B. Algemeene Landsdrukkerij, 's-Gravenhage, 193 p.

Jensen, M.E., R.D. Burman and R.G. Allen (Eds). 1990. Evapotranspiration and Irrigation Water Requirements. ASCE Manual and Reports on Engineering Practice No. 70. ASCE. New York, USA. 335 p.

Kirkham, D. 1957. II. Theory of land drainage, III. The ponded water case. p:139-181. In J. N. Luthin (Ed.). Drainage of Agricultural Lands. Agronomy Monograph No. 7, American Society of Agronomy, Madison, Wisconsin. 620 p.

Klute, A. and C. Dirksen. 1986. Hydraulic conductivity and diffusivity: Laboratory methods. p:687-732. In A. Klute (Ed.). Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods. SSSA Book Series: 5 (formerly Agronomy Monograph 9). Madison, Wisconsin. 1188 p.

Kowald, R. 1968. Technische, hydraulische und bodenkundliche probleme der tonrohrdranung insbesondere in Marschgebieten. Habilitationsschrift, Universitat Giessen (cited as by Trafford and Rycroft, 1974).

Lane, L.J. and M.A. Nearing (Eds.). 1989. USDA-Water erosion prediction project: Hillslope profile model documentation. NSERL Rep. No. 2, USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, Indiana. 265 p.

Mohammad, F. S. 1978. Evaluation of methods for predicting potential evapotranspiration in humid regions. Master of Science Thesis. North Carolina State University, Raleigh, North Carolina. 93 p.

Monteith, J.L. 1981. Evaporation and surface temperature. Quarterly J. Royal Meteorological Society 107(451):1-27.

Nokes, S.E. 1995. Evapotranspiration, Chapter 4, p:91-132. In Ward A. D. and W.J Elliot (Eds). Environmental Hydrology. Lewis Publishers. New York, USA. 462 p.

Ohio Soil Survey. 1960. Auger hole percolation tests conducted by Jim Evans and Ken Donaldson from the field experiment notes of the drainage experiment at the Ohio Agricultural Research and Development Center, North Central Branch, near Sandusky, Ohio.

Patterson, J.M., B.C. Atherton, L. Tornes, R.M. Gehring, J.R. Steiger, J.J. Prenger, L.C. Brown, T.L. Zimmerman, G. Hall and N.R. Fausey. 1997. Modeling drainage response and recommendations for a modern agricultural water management guide. ASAE Paper No. 972125. St. Joseph, Mich.: ASAE. 20 p.

Savabi, M.R., R.W. Skaggs and C.A. Onstad. 1995. Subsurface hydrology, Chapter 6, p:6.1-6.14. In Flanagan, D.C. and M.A. Nearing (Eds). WEPP technical documentation. NSERL Report No. 10, USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, Indiana. 284 p.

Schwab, G.O., T.J. Thiel, G.S. Taylor and J.L. Fouss. 1963.Tile and surface drainage of clay soils. Research Bulletin 935, Departments of Agricultural Engineering and Agronomy, Ohio Agricultural Experiment Station Wooster, Ohio. 47 p.

Schwab, G.O., N.R. Fausey and C.R. Weaver. 1975. Tile and surface drainage of clay soils. Research Bulletin 1081. Ohio Agricultural Research and Development Center, Wooster, Ohio. 37 p.

Schwab, G.O., N.R. Fausey, E.D. Desmond and J.R. Holman. 1985. Tile and surface drainage of clay soils. Research Bulletin 1166, Ohio Agricultural Research and Development Center, Wooster, Ohio. 29 p.

Skaggs, R.W. 1976. Determination of the hydraulic conductivity-drainable porosity ratio from water table measurements. Transactions of the ASAE 19(1):73-80; 84.

Skaggs, R.W. 1978. A water management model for shallow water table soils. Report No. 134. Raleigh, North Carolina. Water Resources Research Institute, Univ. of North Carolina. 175 p.

Skaggs, R.W. 1980. DRAINMOD Reference Report. Methods for design and evaluation of drainage-water management systems for soils with high water tables. North Carolina State University, Raleigh, North Carolina. 177 p.

Skaggs, R.W., N.R. Fausey and B.H. Nolte. 1981. Water management model evaluation for North Central Ohio. Transactions of the ASAE 24(4):922-928.

Taylor, G.S. and N.R. Fausey. 1982. Backfill alterations and drainage of clay soils. p:139-148.In Kriz, G.J. (Ed.). Procedings of the Fourth National Drainage Symposium, ASAE, Chicago, Illinois. 177 p.

Taylor, G.S., E. Stibbe, T.J. Thiel and J.H. Jones. 1970. Hydraulic conductivity profiles of Toledo and Miami Soils as measured by field monoliths. Research Bulletin. 1025. Ohio Agricultural Research and Development Center, Wooster, Ohio. 17 p.

Thornthwaite, C.W. 1948. An approach toward a rational classification of climate. Geographical Reviw 38(1):55-94

Toksoz, S. and D. Kirkham. 1971. Steady drainage of layered soils: II, Nomographs. J. Irrigation and Drainage Engineering, ASCE 97(IR1):19-37.

Trafford, B.D. and D.W. Rycroft. 1974. The natural soil as trench backfill. Technical Bulletin: 74/9, Ministry of Agriculture, Fisheries and Food, England. 9 p.

Van Beers, W.F.J. 1970. The Auger-Hole Method : a field measurement of the hydraulic conductivity of soil below the watertable. ILRI Bulletin 1. Wageningen, Netherlands. 32 p.

Van Schilfgaarde, J. 1963. Design of tile drainage for falling water tables. J. Irrigation and Drainage Engineering ASCE 89(IR2):1-11.

Workman, S.R., R.W. Skaggs, J.E. Parsons and J. Rice (Eds). 1986. DRAINMOD User's Manual. Biological and Agricultural Engineering Department, North Carolina State University, Raleigh, North Carolina. 90 p.

CHAPTER 3

SIMULATING WATER FLOW TO A SUBSURFACE DRAIN IN A LAYERED SOIL

3.1 INTRODUCTION

There are many water table management models developed to predict drain flows. DRAINMOD (Skaggs, 1978) and SWATRE (Belmans et al., 1983) are two popular models used in USA and Europe, respectively. Some other common water table simulation models are EPIC-WT (Sabbagh et al., 1993), GLEAMS-SWAT (Reyes et al., 1994), ADAPT (Chung et al., 1992), and PREFLO (Workman and Skaggs, 1990). To predict drain flow rates, SWATRE uses a finite difference solution of Richards equation (Richards, 1931); EPIC-WT, GLEAMS-SWAT, and PREFLO just use the Hooghoudt equation (Hooghoudt, 1940); and DRAINMOD and ADAPT use the Hooghoudt and Kirkham (Kirkham, 1957) equations in terms of midspace water table height between drains. The Kirkham equation in DRAINMOD and ADAPT is used to predict drainage rates when the profile is saturated and water is ponded on the surface.

Most water table management models incorporate equations that predict drain flow rates as a function of water table elevation using some conceptual shape of the water table drawdown curve from the midpoint between two parallel drains to a drain. For drained soils, several water table drawdown curves given by Salem and Skaggs (1998) are illustrated in Figure 3.1. Curve 1 in Figure 3.1 represents the saturated soil profile condition, in which water is ponded on the soil surface and the water table is at the soil surface. The Kirkham equation in DRAINMOD (Version 4.6) is being used to predict drain flow for this condition of the water table. Curves 4 and 5 illustrate the elliptical shape of water table (drawdown). These are the most common water table conditions for drained soils, and the Hooghoudt equation is used in DRAINMOD and other models for these conditions. Curves 2 and 3 in Figure 3.1 represent transition conditions of the water table from the ponded condition (curve 1) to the elliptical drawdown shape (curve 4). Midspace water tables for curve 2 and 3 conditions are at the soil surface, however, positions of the water table from the midspace to the drain at some level below the surface are different. The midspace water table elevation is the same for both curves, but the shape of these curves are

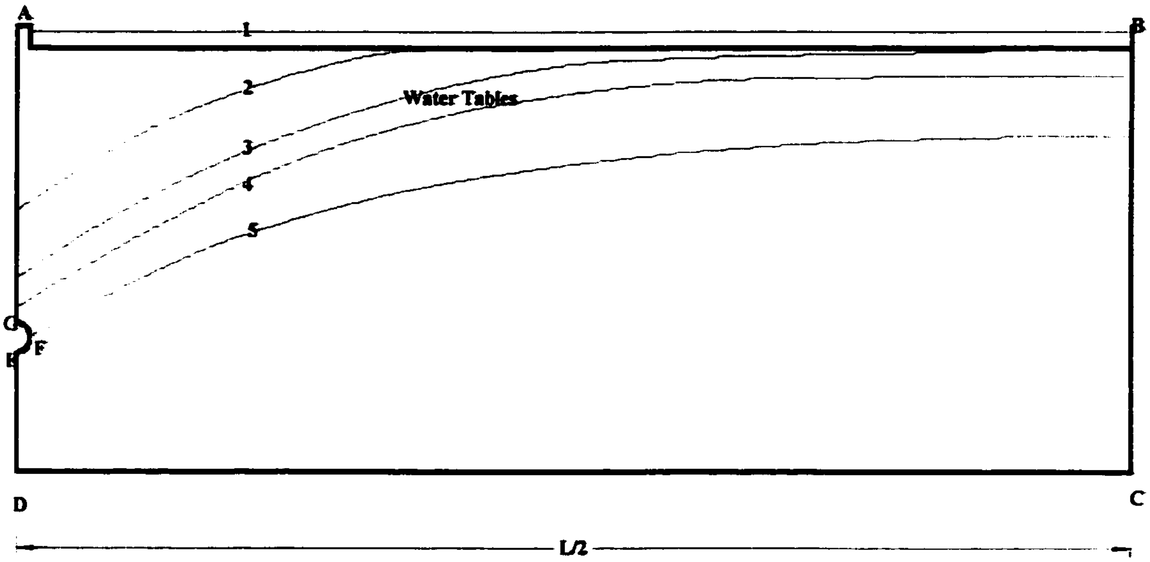

Figure 3.1. Some possible water table positions and shapes at a half drain spacing of subsurface drained soil profile domain, which were given by Salem and Skaggs (1998). Drain tube was represented as a half circle (EFG). Water table curve 1 represents ponded condition, curve 4 and 5 (elliptical shape) represent drawdown condition, and curves 2 and 3 represent transition condition (from ponded to drawdown).

different, therefore, drain flow rates will be different for each of these water table conditions. Salem and Skaggs stated that when the midspace water table is at the surface, the drainage rate might vary between wide limits and is not a unique function of midspace water table elevation. Furthermore, Salem and Skaggs indicated that neither the Kirkham nor the Hooghoudt equation would accurately predict drain flow rates for these water table conditions (curves 2 and 3).

To predict drain flow rates for the water table conditions of curves 2 and 3 (Figure 3.1) in homogeneous soils, Salem and Skaggs (1998) developed the following equation:

$$q = q_k - (q_k - q_o)e^{\beta\frac{H-H_o}{H-H_k}} \quad \text{..........} 3.1$$

where: q is the drainage rate for an average water table depth (cm/hr); q_k is the drain flow rate predicted by the Kirkham equation for a completely saturated soil profile (cm/hr); q_o is the drain flow rate corresponding to H_o (cm/hr); β is a fitting parameter; H is the average water table elevation from impermeable layer (cm); H_o is the upper limit average water table elevation at which the Hooghoudt equation accurately predicts drainage rate (cm); and H_k is the value of q_k corresponding to the maximum water table elevation (soil profile depth) (cm). To develop Equation 3.1, Salem and Skaggs used the SWMS-2D program (Simunek et al., 1994) which numerically solves the Richards equation (Richards, 1931) for saturated and unsaturated water flow and the convection-dispersion equation for solute transport. Finally, Salem and Skaggs developed an algorithm to predict drain flow rates in terms of the average water table elevation between two parallel drains in place of the midspace water table elevation. The algorithm combines a classical solution of the Kirkham equation for ponded conditions, the Hooghoudt equation for drawdown conditions, and empirical Equation 3.1 for transition conditions. The algorithm by Salem and Skaggs was developed for artificially drained homogenous soils.

The specific objectives of the work presented in this chapter are 1) simulate drain flow into subsurface drainage pipes for a layered soil profile using HYDRUS-2D (Simunek et al., 1996), and 2) develop an equation similar to that of Equation 3.1 that predicts drain flow rates for transition conditions of water table for a layered soil. The success of reaching objective 2 will be based upon the results of the work for objective 1.

3.2 LITERATURE REVIEW

Numerical methods are frequently used to solve problems for water flow to drains in a soil profile. The solutions may be based on finite difference, finite element, or some other kind of boundary approximation technique. The rate of water movement into drains depends on the hydraulic conductivity of the water flow domain of the surrounding soil, drain spacing and depth, soil profile depth, and water table elevation. Many approximate equations such as Richards (Richards, 1931), Boussinesq (Smith, 1985), Ernst (Ernst, 1962), Hooghoudt (Hooghoudt, 1940), Kirkham (Kirkham, 1957), van Schilfgaarde (van Schilfgaarde, 1963), Hammad (Hammad, 1962), etc., were developed to solve this problem. The Richards and Boussinesq equations are solved numerically.

Skaggs (1980) states that water movement to drains can best be quantified by solving the Richards equation for two-dimensional flow. In spite of input and computational time requirements which in the past have probably prohibited the practical use of these methods, numerical solutions provide very useful means of evaluating approximate equations that compute drainage flow (Skaggs, 1980). In the following paragraphs of this section, several drain flow simulation studies using finite element, finite difference, or some boundary model techniques are summarized.

Vimoke et al. (1963) represented the drain tube as a single grid point in their electrical resistance network studies. They compared the drain flows from their networks to analytic solutions of the Kirkham equation. They stated that the network data generally deviates less than 2% if a logarithmic expression is used to calculate network resistance adjacent to the drain.

Pickens et al. (1979) used a finite element method based on a Galerkin technique (Simunek et al., 1994) to formulate the two-dimensional transient movement of water and solutes in saturated or partially saturated non-uniform porous media. The flow portion of the model was tested by comparing model results with experimental data and finite difference model results for transient flow in an unsaturated sand column. The solute transport portion of the model was evaluated by comparing its results with an analytical solution. The model was applied to a hypothetical case of simulating salt and water movement in a subsurface drained sandy soil. Pickens et al. stated that the results showed the development of distinct solute leaching patterns in the soil as drainage proceeded.

Merva et al. (1983) developed a finite element model based on a formulation given by Segerlind (1976) to solve Laplace's equation for a non-homogenous layered soil. The model needed the soil characteristics curve for the surface layer, and the hydraulic conductivity of as many as three soil layers and a trench backfill zone to predict locations of the water table. The model predicted the position of the water table for a drainage system in Toledo silty clay using data from Fausey (1975), Schwab et al. (1963), and Taylor et al. (1961). Merva et al. stated that the water table depth predictions were of an acceptable accuracy. Also, while modeling the three layered Hoytville silty clay loam (Taylor et al., 1961) with a trench backfill (as one layered homogenous soil), they found that the hydraulic conductivity of the backfill does not seem to affect the critical time (arbitrarily chosen as 30 h) to drop the water table from the surface to 30 cm (11.8 in), and thus, they stated that a very low value of hydraulic conductivity (2.7 to 4.2 times lower than the hydraulic conductivity of the first layer) in the second layer (such as might be found in a plow pan) of a three layered soil does seriously restrict the permissible drain spacing.

Fipps et al. (1986) studied four different methods to represent drain tubes in finite element solutions to the Richards equation (Richards, 1931). These methods were : 1) modeling a hole in the finite element mesh equal in size to the effective radius of the drain; 2) using the Kirkam equation to specify the flux at a single nodal point representing the drain; 3) specifying the hydraulic head at a single node representing the drain; and 4) applying the resistance adjustment method of Vimoke and Taylor (1962) by adjusting the hydraulic conductivity values of the elements around a single node representing the drain. After comparison of solutions for steady state, transient, and interceptor drainage, they stated that applying the resistance adjustment method of Vimoke and Taylor (1962) more accurately predicted drain flow rates and hydraulic heads than did predictions using the Kirkham equation.

To simulate water movement from a variably saturated soil into a drain pipe, Martinez et al. (1989) used a computer program developed by Kaluarachchi and Parker (1987) to numerically solve the Richards equation. Martinez et al. represented the drain tube as a hole with an effective drain radius. As a boundary condition, they simulated the drain as a seepage face. In the design of the grid, they used rectangular elements for the soil region far away from the drain and triangular elements around the drain. They compared the finite element results with measured drain flow data from southeast Indiana. As a result, they stated that the finite element model simulated drain flow hydrographs reasonably well for both 5 and 10 m (16.4 and 32.8 ft) drain spacings, except that their model underestimated peak flows.

Yu and Konyha (1992) developed a boundary model solution to the Laplace equation to determine flow nets in soils with drainage and subsurface irrigation systems. Their model predicted water table position, hydraulic head loss at the drain, as well as flux and potential along the boundary. They also indicated that their program could analyze flow problems involving layered soils, trench effects, subsurface irrigation and drainage. Flows in layered soils and in trenches are solved by defining separate-homogeneous sub domains coupled by conditions at the interface. Drain tubes were represented as open tubes of their effective radius. They used ten nodes along the circumference of the drain. Yu and Konyha stated that their model's water table predictions agreed very closely with those predicted using the Hooghoudt equation.

Rogers et al. (1995) used numerical solutions of Richards equation to derive flow nets and velocity distributions for two shallow soil profiles for saturated flow, steady rainfall seepage, and a case with a falling water table and flow to shallow drains. In their study, they simulated the drain as a single node in the mesh by the procedure of Vimoke and Taylor (1962) as modified by Rogers and Fouss (1989). They also used the Hooghoudt equation to calculate the midspace water table elevation for a given drain flow rate and compared it with their numerical results. The predictions with the Hooghoudt equation tended to track the steady state rainfall case, but tended to predict higher drain flow rates for a given midspace water table elevation.

As stated before, to characterize drain flow rate as a function of water table elevation, Salem and Skaggs (1998) used SWMS-2D (Simunek et al., 1994), which solves the Richards equation by using a finite element technique. In their study, drain was represented as a completely permeable half circle with radius equals to the effective radius, and assumed to run half full. Boundaries AG, BC, CD, and DE given in Figure 3.1 were represented as having no flow; GF had constant hydraulic head with the pressure head at the lowest point in the drain having a value equal to the effective radius of the drain, and for the rest of the drain boundary the pressure head decreased linearly to zero at point F; boundary FE was considered as a seepage face; and boundary AB was simulated as a Neuman type constant flux. To evaluate the solution, model results were compared against the Kirkham equation for a completely saturated soil profile with water ponded on the surface. Salem and Skaggs stated that the model solution for both drain flow rate and pressure head at different locations in the flow domain matched the Kirkham equation solution, with an error not exceeding 5% when the drain radius was small[1] compared to the problem geometry, and errors up to 20% when the drain effective radius was large in comparison to drain depth or depth to impermeable layer. As mentioned before, using the results from their study, Salem and Skaggs developed Equation 3.1 to predict drain flow rates for the transition conditions of a water table in a homogeneous soil.

For the current work, similar drain tube and boundary conditions with in the soil profile domain as defined by Salem and Skaggs (1998) were used.

3.3 MATERIALS AND METHODS

In this research, the HYDRUS-2D model (Simunek et al., 1996) was used to determine drain flow rate as a function of midspace water table elevation above the drain. The HYDRUS-2D model is the latest commercial version of the SWMS-2D program simulating water flow and solute transport in two- and three-dimensional axisymmetric variably saturated porous media. The model is Microsoft Windows based and supported by an interactive graphics-based interface for data processing, generation of a structured mesh, and graphic presentation of the results. The model includes a mesh generator for unstructured finite element grids, MESGEN-2D.

The HYDRUS-2D model numerically solves the Richards equation for saturated and unsaturated water flow to drains. The modified form of the Richards equation used in the model is:

$$\frac{\partial Q}{\partial t} = \frac{\partial}{\partial x_i}\left[K(K_{ij}^{A} \frac{\partial h}{\partial x_j} + K_{iz}^{A}) \right] - S \text{...} 3.2$$

---

[1] Although Salem and Skaggs (1998) did not quantify small and large effective radii, values they cite elsewhere were r = 1, 5, and 30.

where: Q is the volumetric water content (L^3L^{-3}); h is the pressure head (L); S is a sink term (T^{-1}); x_i (i=1,2) is a spatial coordinate (L); t is time (T); K_{ij}^A is a component of a dimensionless anisotropy tensor K^A; and K is the unsaturated hydraulic conductivity function (LT^{-1}) given by:

$$K(h,x,z) = K_{sat}(x,z)K_r(h,x,z) \quad\ldots\ldots\ldots\ldots 3.3$$

where: K_r is the relative hydraulic conductivity; and K_{sat} is the saturated hydraulic conductivity (LT^{-1}).

Data from the drainage experiment of Schwab et al. (1963; 1975; and 1985) at the Ohio Agricultural Research and Development Center (OARDC) North Central Branch, near Sandusky, Ohio, was used as input to the model. In the current research, the soil domain with the drain is represented similar to that presented by Salem and Skaggs (1998) as follows. For the subsurface drainage system at this research site, the drain spacing was 12.2 m (40 ft), the drain depth was 90 cm (35.4 in), and one half the drain spacing, L/2, is equal to 6.1 m (20 ft). The same soil profile depth (165 cm; 65 in) simulated by Skaggs et al. (1981) and used previously in Chapter 2 was also used in this chapter.

The HYDRUS-2D model was used to develop drain flow-water table elevation curves to be compared to two curves: i) obtained using the empirical equation by Hoffman (1963) transformed to metric units:

$$LogQ = \frac{H^2}{1935.42} - \frac{H}{56.44} - 1.865 \quad\ldots\ldots\ldots\ldots 3.4$$

where: Q is the drain flow depth (cm/day); and H is the midspace water table elevation (cm) above the drain; and ii) obtained using the following form of the Kirkham (Eq. 3.5) and Hooghoudt (Eq. 3.6) equations (Skaggs, 1980):

$$Q = 4\pi K_e(t+b-r)/gL \quad\ldots\ldots\ldots\ldots 3.5$$

$$Q = \frac{K_e(8d_eH + 4H^2)}{L^2} \quad\ldots\ldots\ldots\ldots 3.6$$

where: K_e is the equivalent saturated hydraulic conductivity (cm/day); t is the depth of water on the soil surface (cm); b is the depth to the drains (cm); r is the radius of the drain tube (cm); H is the midspace water table elevation; d_e is the equivalent depth from the drain to the impermeable layer; and L is drain spacing (cm); and g is

$$g = 2\ln(\frac{\tan(\pi(2d - r)/4h)}{\tan(\pi r/4h)}) \qquad 3.7$$

where: h is the depth of soil profile (cm).

The English unit version of Equation 3.4 (previously given as Equation 2.12 in Chapter 2) was found as the best empirical solution by Hoffman (1963) using data from the drainage experiment site described by Schwab et al. (1963; 1975; and 1985). This equation was developed using the measured midspace water table elevations above the drain and the corresponding drain flow rates for the years of 1960, 1961, and 1962 for the Toledo silty clay soil. Therefore, an assumption was made that Equation 3.4 best describes the drain flow-water table elevation relationship. Remember that the drain flow-water table elevation curves using the Equation 3.4 (Equation 2.12 in Chapter 2; English unit form of Eq. 3.4) and the Kirkham-Hooghoudt equations were previously developed and illustrated in Figure 2.22 (Chapter 2). The work in Chapter 2 used subsurface drainage system input parameters (Table 2.1 in Chapter 2) with van Schilfgaarde equation estimated K_{sat} values (Table 2.4 in Chapter 2) for use in DRAINMOD. The curves given in Figure 2.22 (Chapter 2) were used again in this chapter.

This component of the research was conducted to help determine the ability of the model to predict drain flow-water table elevation relationships and considered two cases of water loss at the soil surface: with evapotranspiration and with no evapotranspiration. The model was then used to evaluate the effect of backfill on drain flow-water table depth relationships with and without evapotranspiration.

In a preliminary analysis, the range of K_{sat} values (Table 2.4 in Chapter 2) used in Chapter 2 were also used here to select the best set of values to be used in the HYDRUS-2D simulations. These analyses showed that the best drain flow-water table elevation curve generated by HYDRUS-2D compared to the curves obtained using Equation 3.4 and the Kirkham-Hooghoudt equations were obtained with the core method estimated saturated hydraulic conductivity values (K_{sat}) from Schwab et al. (1963). These K_{sat} values were previously given in Appendix C. Remember from Chapter 2 that DRAINMOD simulations using the van Schilfgaarde equation estimated K_{sat} values produced the smallest average deviation between predicted and measured drain flows and runoff.

The drain in Figure 3.1 was represented as a completely permeable half circle (EFG) with radius equal to the effective radius (0.48 cm) (0.19 in) of the drain. The upper boundary AB was represented as a Neuman-type constant flux boundary for two conditions, with and without evapotranspiration. The boundaries BC, CD, DE, and GA were represented as no flow boundaries. To prevent water entry into the profile from the drain, the boundary represented by the drain (EFG) was considered as a seepage face with pressure head equal to zero at the beginning of the simulation. These are the same boundary conditions as used by Salem and Skaggs (1998), except for the seepage face. The use of the seepage face was not described by Salem and Skaggs (1998), but was suggested by Simunek (1998). The generated finite element mesh layout for the soil profile domain and a detailed view in the vicinity of the drain pipe are given in Figures 3.2 and 3.3, respectively. The meshes were generated using the model's automatic mesh generator program called MESGEN-2D. In the construction of the mesh, denser and small sized elements in the vicinity of the drain and at the surface, where most of the flow lines are concentrated, were generated. The total element number generated was 3695.

The HYDRUS-2D model needs the following input data (Simunek et al, 1996): number of layers in the soil profile, initial water table depth, residual and saturated water contents of each soil layer, parameters of α and n (respectively, the coefficient and the exponent in the soil water retention function), saturated hydraulic conductivity of each soil layer, root water uptake parameters, root distribution in the profile, and evaporation and transpiration rates during the simulation time. Table 3.1 lists some of these input data. HYDRUS-2D outputs drain flow in units of cm^2/hr per unit length of lateral.

The dominant soil at the OARDC North Central Branch site was Toledo silty clay. Schwab et al. (1963) reported that Toledo silty clay consists of seven horizons with in a soil profile depth of 165 cm (65 in) (Appendix C, Table A1). For this reason, the soil profile was divided into seven layers with respect to the horizon depths given by Schwab et al (Appendix C, Table A1). The K_{sat} values for the top five soil layers were taken from Schwab et al. (Appendix C, Table A1). The K_{sat} values for the bottom two layers were taken from Skaggs et al. (1981), and are actually equivalent hydraulic conductivity values (K_e) when the midspace water table depths are at 101.60 and 165 cm (40 and 65 in) from the soil surface (see footnote in Table 2.2 in Chapter 2). In this study, it was also assumed that these K_e values are equal to the K_{sat} values for the last two soil layers.

The residual water content (Q_r), and the parameters α and n in the soil water retention curves were obtained using the RETC program (Van Genuchten et al., 1991) with the soil water

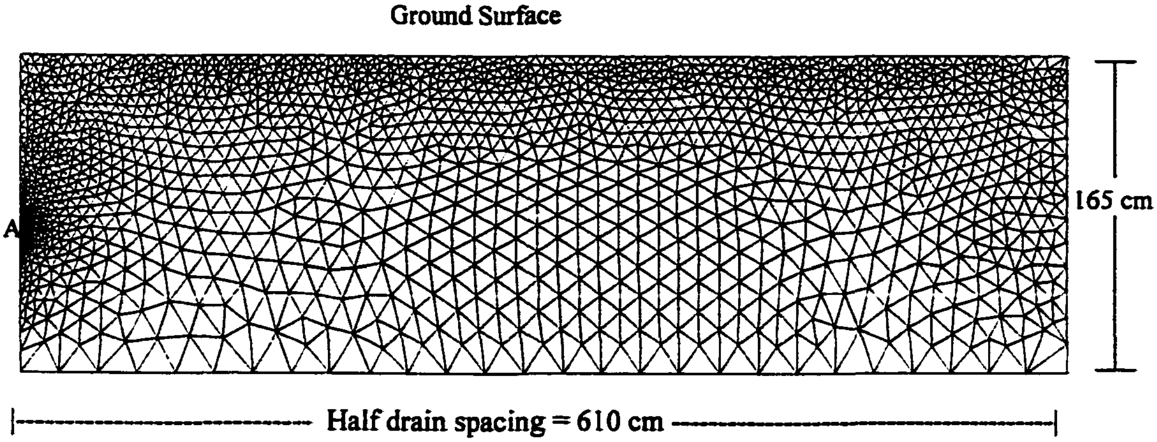

Figure 3.2. Finite element mesh layout for the half drain spacing of the Toledo silty clay soil profile depth of 165 cm (65 in). Drain pipe is located on the left side of the profile (A), it is 90 cm (35.4 in) below the surface.

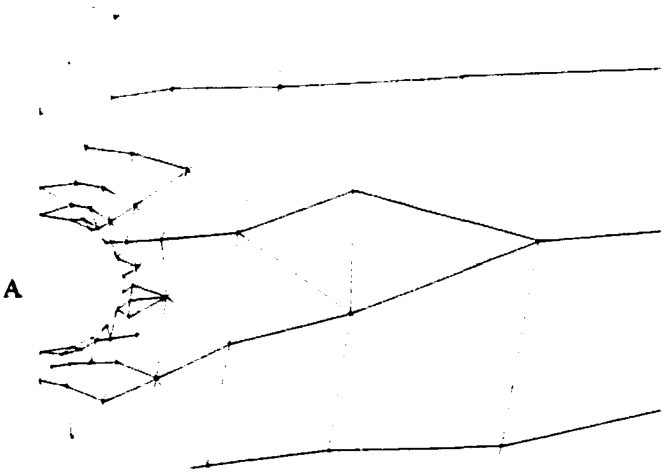

Figure 3.3. Detail of the elements near the drain of the finite element mesh in Figure 3.2. Drain pipe is a 10 cm (4 in) clay tile with 0.32 cm (1/8 in) cracks, and the radius = effective radius of 0.48 cm (0.2 in) from Workman et al.(1986).

Horizon	Depth (cm)	Q_s (cm^3/cm^3)	α (1/cm)	n	K_{sat} (cm/hr)
A_p	0 – 20	0.536	0.0044	1.1837	2.540
B_1	20 – 33	0.536	0.0044	1.1837	0.296
B_{21}	33 – 51	0.536	0.0044	1.1837	0.138
B_{22}	51 – 76	0.470	0.0032	1.1252	0.095
B_{23}	76 – 96	0.470	0.0032	1.1252	0.169
C_{11}	96 – 127	0.470	0.0032	1.1252	0.01*
C_{12}	127 – 165	0.470	0.0032	1.1252	0.01*

*: From Skaggs et al. (1981)

Table 3.1. Saturated soil water contents (Q_s), coefficient α and exponent n for the soil water retention function, and saturated hydraulic conductivity (K_{sat}) for the seven soil layers of Toledo silty clay. The first five soil layers depth and hydraulic conductivity data were the same as presented in Table 2.5 in Chapter 2. The last two layers depths were taken from Schwab et al., (1963) (Appendix C, Table A1).

retention data from Skaggs et al. (1981) (Appendix A, Figure 1). Values for Q_r, α, and n were obtained by fitting the soil water retention function to the soil water retention data. The coefficients of determination (R^2) for these fits are 0.94 and 0.99 for the top and bottom curves of Skaggs et al. (Appendix A, Figure 1), respectively. The top curve data, for the 5-15 cm (2-6 in) depth increment, were used for the first three layers of the soil profile, and the data from the bottom curve, for the 50-75 cm (19.7-29.5 in) depth increment, were used for the remaining four soil layers.

The root water uptake parameters are: i) the value of pressure head below which roots start to extract water from the soil (-10 cm of water); ii) the value of the limiting pressure head below which the roots can not extract water at an assumed upper potential transpiration rate of -25 cm of water; iii) the same as for ii except for an assumed lower potential transpiration rate of -1000 cm of water; iv) the value of the pressure head below which root water uptake ceases, -15000 cm of water; and v) the assumed upper and lower transpiration rates of 0.25 and 0.1 cm/day (0.1 and 0.04 in/day), respectively. A 40 cm (15.7 in) corn root depth at the middle of growing season was also assumed and used as the root distribution depth. Furthermore, when evapotranspiration was considered, an assumed constant transpiration rate of 0.01 cm/hr (0.004 in/hr) and evaporation rate of 0.002 cm/hr (0.8×10^{-3} in/hr) were used during the entire simulation time periods of 130 hours. For all HYDRUS-2D simulations, it was assumed that the initial water table was ponded on the surface (0.1 cm; 0.04 in).

To evaluate the effect of backfill on drain flow and on the shape of the drain flow-water table elevation curve, the backfill was divided into five layers. Figure 3.4 shows these layers for one-half the drain spacing as shown in Figure 3.1. All the input values used for the soil layers except K_{sat} values were also used for the layers of backfill. Forty years after installation of the drains at this site, soil samples from the backfill at different depths were collected and analyzed for K_{sat}. The measured saturated hydraulic conductivity values with their corresponding soil sample depths are given in Table 3.2 along with the original core data from Schwab et al. (1963). These depths were used in HYDRUS-2D as depths of backfill layers.

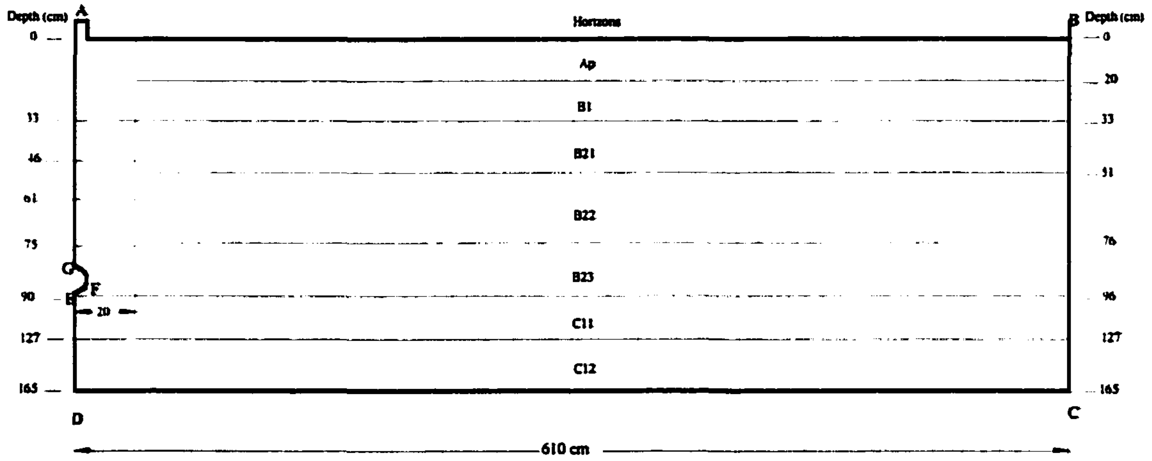

Figure 3.4. Layers in backfill and half drain spacing domain (not in scale) of Toledo silty clay at the drainage experiment station of OARDC North Central Branch, near Sandusky, Ohio.

3.4 RESULTS AND DISCUSSIONS

3.4.1 Objective 1: Simulating Drain Flow with HYDRUS-2D

The results of the HYDRUS-2D model predictions compared to those using Equation 3.4 and the Kirkham-Hooghoudt equations are presented in this section for two cases: case 1) with and without evapotranspiration (ET) and no effect of backfill (the case shown in Figure 3.4 but without a backfill condition); and case 2) with and without ET and with a backfill condition. All HYDRUS-2D results presented hereafter used K_{sat} values for the top five soil layers estimated from the soil core data of Schwab et al. (1963) and K_{sat} values for the bottom two soil layer from Skaggs et al. (1981).

3.4.1.1 Case 1

The conceptual system presented in Figure 3.4, but without the backfill conditions, was simulated using HYDRUS-2D[2]. The results of this simulation provided drain flow-water table elevation relationships that were then compared to those predicted using Equation 3.4 and the Kirkham-Hooghoudt equations. These predicted water table elevations were the height of the water table above the centerline of the drain pipe at the midspace between two parallel drains. Figure 3.5 illustrates the drain flow-water table elevation relationships for these three prediction methods. The HYDRUS-2D curve was produced for the case without any ET. There was no difference in the HYDRUS-2D curves for no ET and for an ET rate of 0.3 cm/day. Note that in Figure 3.5 that at the point where the water table elevation is at 90 cm above the drain centerline, the water table is at the soil surface at the midspace location. It was expected that the only difference between these three curves would be when the water table was close to the surface as noted by Salem and Skaggs (1998) (Appendix I, Figure 2).

As stated above, there was no effect of ET on the drain flow-midspace water table elevation curve, however, with the ET rate of 0.3 cm/day, drain flow approached zero after about 93.5 hours from the beginning of the simulation (not shown). Without ET, drain flow continued after 130 hours from the beginning of the simulation. At the beginning of simulation, the water table was on the surface (90 cm point on Figure 3.5), and HYDRUS-2D underpredicted drain flow compared to Equation 3.4 and the Kirkham-Hooghoudt equations for water table elevations above 70 cm (27.5 in). This is mainly because of the very small contribution of drainage from the first soil layer in the early time intervals. Maybe for this reason, Merva et al. (1983) reached their result indicating that a very low value of hydraulic conductivity in the second layer seriously restricted the permissible drain spacing. However, after the water table elevation decreased by approximately 20 cm (7.9 in), HYDRUS-2D predictions were very close to those using Equation

---

[2] : To be consistent with the drain flow units of cm^2/hr per unit length of lateral that is standard output from HYDRUS-2D, the flow rate in cm/day calculated using Equations 3.4 and Kirkham-Hooghoudt equations was converted to cm^2/hr. To convert cm/day to cm^2/hr, cm/day was multiplied by half of the drain spacing (610 cm) which was modeled in HYDRUS-2D, and then divided by 24 (hours in a day).

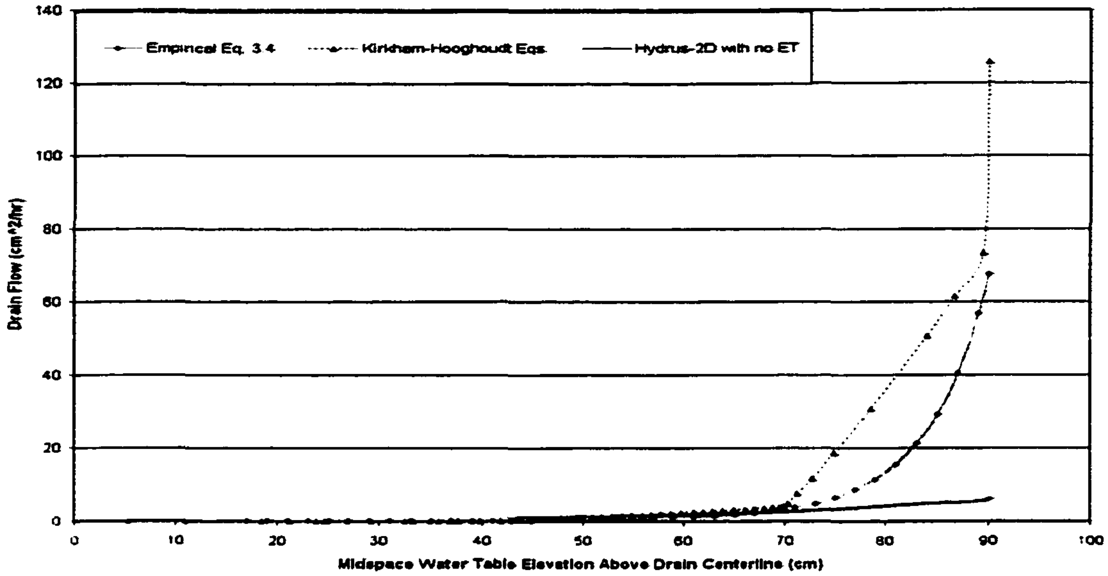

Figure 3.5. Drain flow-water table elevation relationship using HYDRUS-2D with no backfill condition and no ET compared to those using empirical Equation 3.4 and the Kirkham-Hooghoudt equations for Toledo silty clay soil.

3.4 and the Kirkham-Hooghoudt equations. Remember that these three curves are not based on the same time frame, which is not shown in Figure 3.5.

Figures 3.6 and 3.7 show the spatial distribution of pressure heads and velocity vectors when midspace water table elevations above the drain centerline are at 87 and 66 cm (34.2 and 26 in), respectively. In (a) and (b) in Figure 3.6, the isolines of pressure head in the top layer are almost flat suggesting that subsurface drainage did not affect much water loss from this layer to the drainage tube. In addition, Figure 3.7 illustrates that most of the water in the top layer tends to flow horizontally along this layer until it reaches a point over the drain, where the flow direction becomes vertical. These results could be anticipated since the ratio of the hydraulic conductivity of the top layer to the second layer (2.540/0.296 cm/hr; 1/0.116 in/hr) was 8.6. Fausey (1977) states that whenever this ratio reaches a value of five, the interface of these two layers serves effectively as an impermeable boundary for saturated flow. Therefore, the water in the top soil layer does not move vertically to the second layer very quickly, and subsequently water flow in the top layer will be horizontal until it reaches a point over the drain.

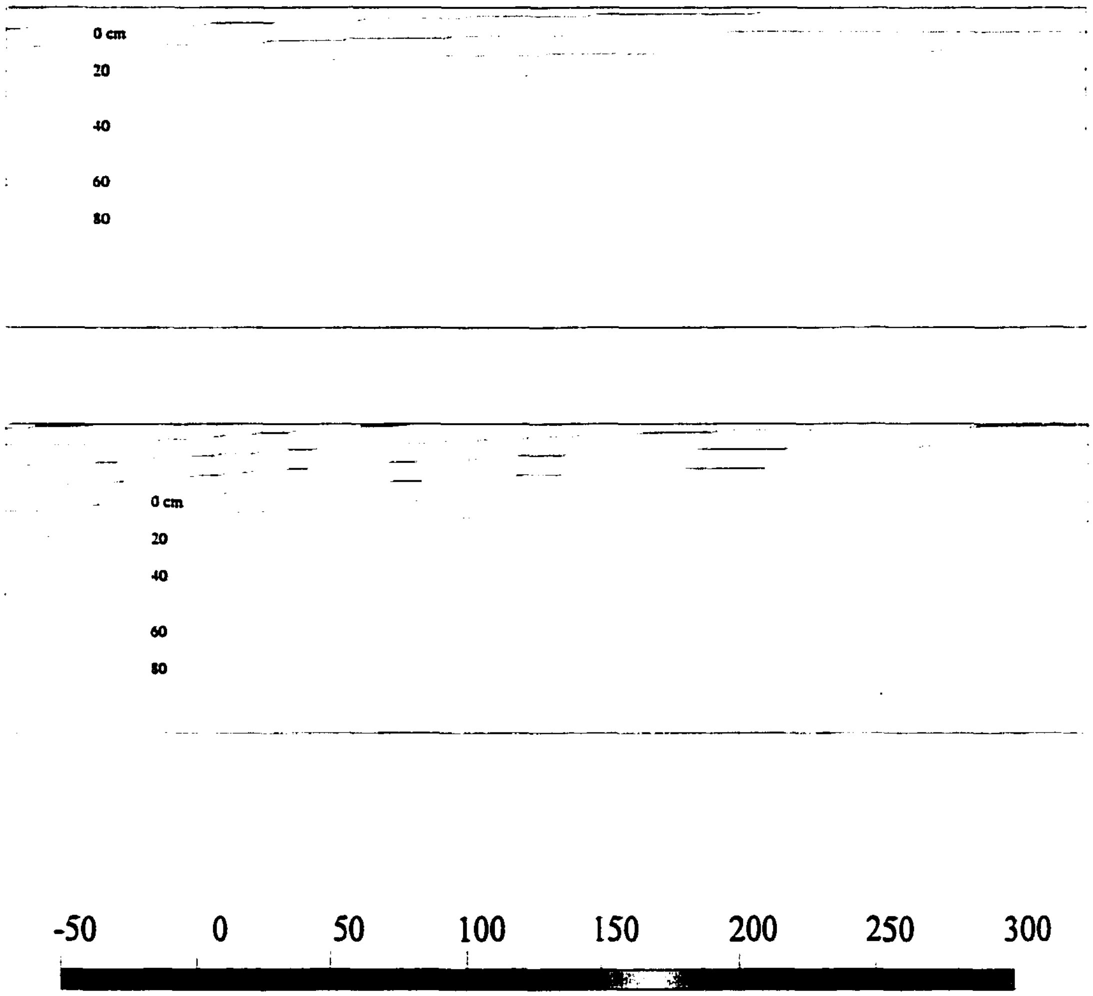

Figure 3.6. Spatial distribution of pressure heads (cm of water) in the half drain spacing of Toledo silty clay soil profile domain when midspace water table elevations above drain are 87 and 66 cm (34.2 and 26 in). The curves of 0 cm pressure heads show water table locations. The scale of pressure heads is described with bottom figure.

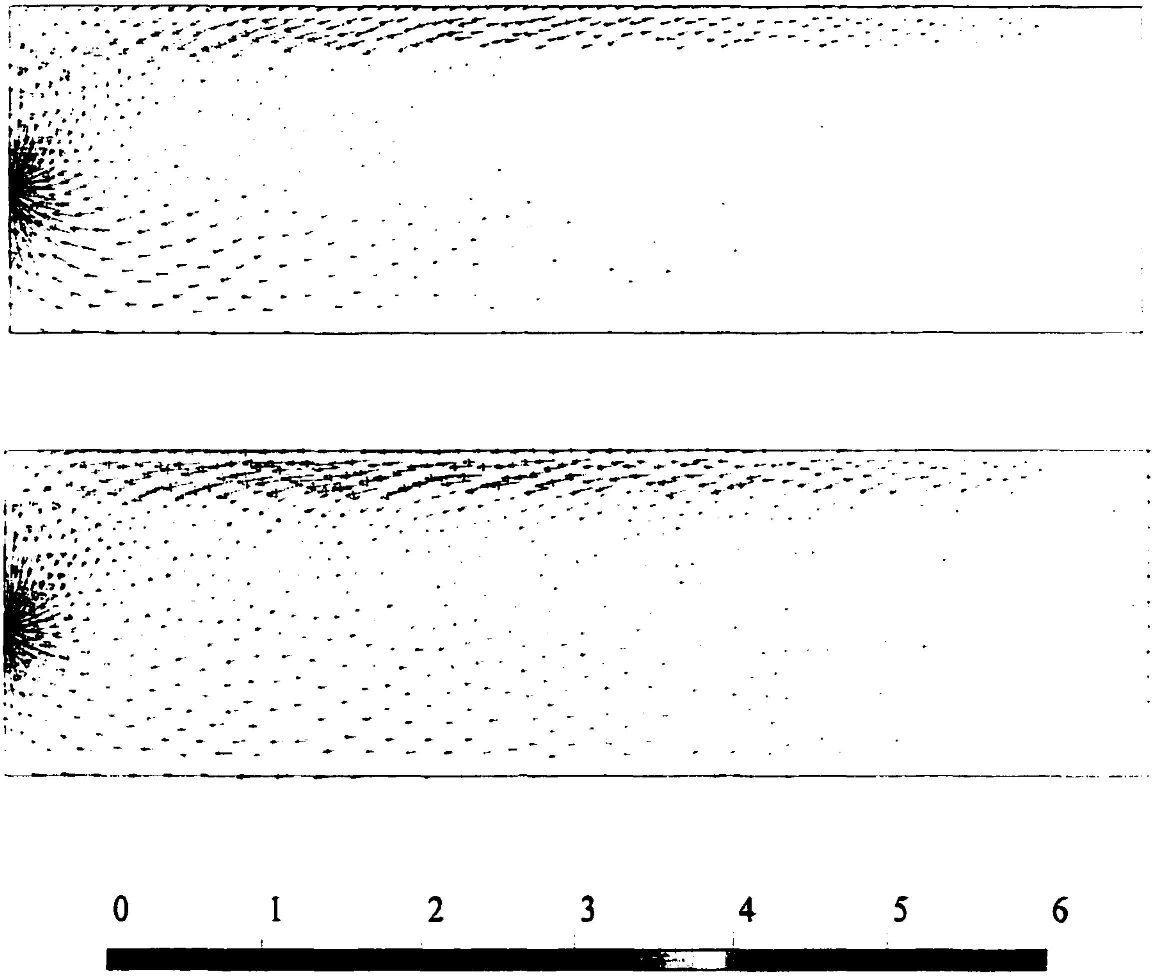

Figure 3.7. Spatial distribution of velocity vectors for one-half drain spacing for the Toledo silty clay soil profile domain when the midspace water table elevations above the drain centerline are at 87 (a) and 66 (b) cm (43.1 and 26 in). The scale figure (c) shows the magnitude of velocity (cm/hr) of moving water.

Most water flow from the top layer to the second layer occurs through the short interface distance between the top and second layer in the region just above the drain (Fig. 3.7). The effect of a reworked ditch or backfill at this short interface distance possibly helps provide a better hydraulic connector between the drain and the shallow soil layers. For this reason, HYDRUS-2D was used to simulate backfill in the soil profile domain in the next case.

3.4.1.2 Case 2

The drainage system installed in 1958 at this site was trenched and the blinding was the original excavated material. A picture of the trenching and blinding at the site was given by Schwab et al. (1963) (Appendix J, Figure 4). They stated that the topsoil included alfalfa stems and roots was placed about 15.2 cm (6 in) above the top of the concrete tile. Initially to simulate the backfill, the saturated hydraulic conductivity values for the backfill soil layers given in Table 3.2 were used in HYDRUS-2D. The resulting drain flow-midspace water table elevation curves are given in Figure 3.8 along with those using Equation 3.4 and the Kirkham-Hooghoudt equations. There is little difference between the HYDRUS-2D curves given in Figure 3.5 for the no backfill simulation and Figure 3.8 for the backfill simulation. In the backfill simulation scenario, the model produced slightly higher drain flow rates than those obtained without simulating backfill when the midspace water table elevation was greater than 70 cm (27.5 in). However, the large difference between the curves from HYDRUS-2D and the curves from Equation 3.4 and the Kirkham-Hooghoudt equations remain when midspace water table elevation is greater than 70 cm. Note that the ratio of saturated hydraulic conductivity for the top layer to the second layer is much greater than five (96.3), and therefore the same interface problem discussed earlier was intensified here. From this analysis, it appears that the backfill did not perform the hydraulic connector function between the upper soil layer in the backfill and the drain tube because of the very low K_{sat} values in the backfill soil layers. In the previous analysis, the original soil core data from Schwab et al. (1963) were used assuming the conductivity in the trench was the same as in the undisturbed soil profile. In this analysis, soil core data forty years after installation were used. Again, the effect of ET in this HYDRUS-2D simulation was very small (not shown).

Taylor and Fausey (1982) stated that on a long term basis, drainage of clay soils is always inadequate. Their results on Toledo silty clay indicated that the trenched and backfilled condition helped increase drain flow rates by as much as 100 to 200% compared to drains with no backfill

Core (1963)+ (Original undisturbed site data)		Recent Core Data (1998)* (Backfill)	
Depth (cm)	K_{sat} (cm/hr)	Depth (cm)	K_{sat} (cm/hr)
0-20	2.540	0 – 33	1.541
20-33	0.296	33 – 46	0.016
33-51	0.138	46 – 61	0.063
51-76	0.095	61 – 75	0.193
76-96	0.169	75 – 96	0.307

+: Core samples collected and analyzed by Schwab et al. (1963) (Table A1 given in Appendix C) for undisturbed soil.

*: Core samples collected from the trench backfill in 1998, 40 years after tile installation.

Table 3.2. Saturated hydraulic conductivity (K_{sat}) values of Toledo silty clay at the drainage experiment of OARDC North Central Branch, near Sandusky, Ohio.

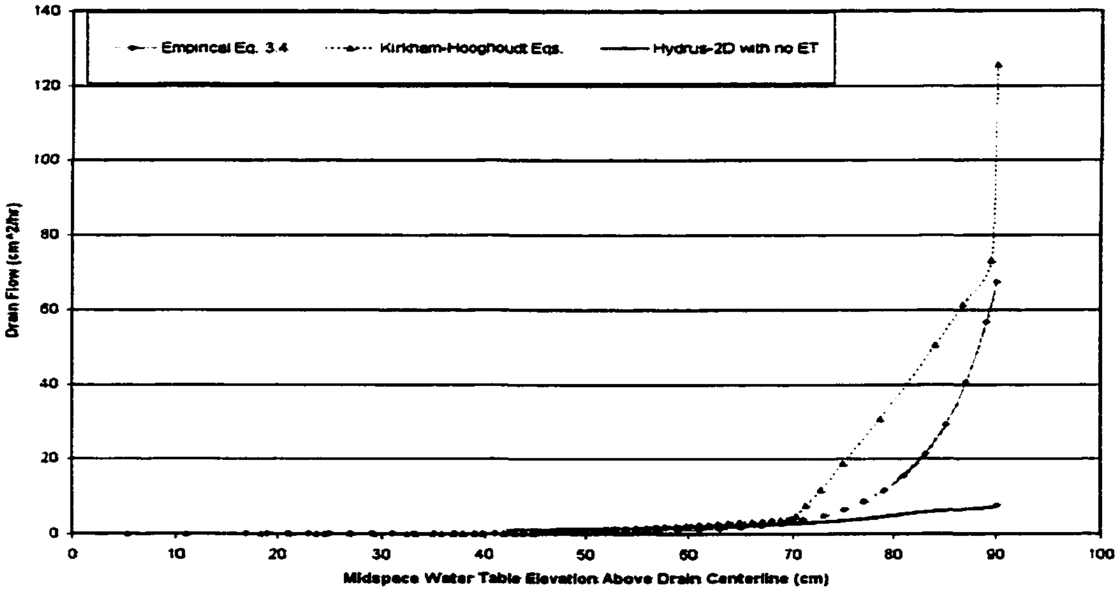

Figure 3.8. Drain flow-water table elevation relationship using HYDRUS-2D with measured backfill K_{sat} values and no ET compared to those using the empirical Equation 3.4 and the Kirkham-Hooghoudt equations for Toledo silty clay soil.

alteration. They also stated that the greater flow rates for the backfilled drains persisted for four years after installation; however, a small but consistent decline in flow rate appeared for the last 3 years. This decrease in drain flow probably resulted from soil consolidation, and subsequently a decrease in saturated hydraulic conductivity in the backfill. Trafford and Rycroft (1974) stated that changes in saturated hydraulic conductivity depend on the initial condition, the degree of stability to water of the soil, climatic regimes and other factors.

To further evaluate the backfill effect, a range of saturated hydraulic conductivity values were assigned to the backfill layers, using the maximum saturated hydraulic conductivity value of 2.540 cm/hr (1 in/hr) from Table 3.1 (undisturbed value of top soil layer) as an upper limit for each layer. A number of combinations were evaluated. The resulting curves from HYDRUS-2D were compared with those from Equation 3.4 and the Kirkham-Hooghoudt equations (not shown). Overall, the best HYDRUS-2D curve was obtained when the K_{sat} value of 2.540 cm/hr was used for all the backfill soil layers. This curve, shown in Figure 3.9, again illustrates how well HYDRUS-2D produces drain flow results that match those of Equation 3.4 and the Kirkham-Hooghoudt equations for all midspace water table elevations below 70 cm (27.5 in). At water table elevations greater than 70 cm, there is substantial improvement over the HYDRUS-2D results shown in Figures 3.5 and 3.8. From Figure 3.9, in the range of water table elevations from 70 to 90 cm, the Kirkham-Hooghoudt equations over predict drain flow by 82% and HYDRUS-2D underpredicts by 52%.

The effect of ET on drain flow simulation is somewhat more clear than in the previous two analyses. With an ET rate of 0.3 cm/day (0.12 in/day), HYDRUS-2D produced slightly larger drain flows at the higher water table elevations. Figure 3.10 shows this difference. To further illustrate the effects of ET rate on the shape of drain flow-water table elevation curve, HYDRUS-2D was run one more time with the K_{sat} values of backfill soil layers are equal 2.540 cm/hr, and with the ET rate of 0.4 cm/day (0.16 in/day). The resulting curve was also shown in Figure 3.10. With larger ET rates, larger drain flows were obtained for the same midspace water table elevation especially when the midspace water table elevations were greater than 70 cm. Salem and Skaggs (1998) stated that this was due to changes in the shape of the water table profile. In the case of higher ET rates, the water table tended to be flatter with steeper gradients near the drain. In addition, when larger ET rates are used in HYDRUS-2D, the difference between the HYDRUS-2D curves and those obtained using Equation 3.4 and the Kirkham-Hooghoudt equations for water table elevations greater than 70 cm decreased.

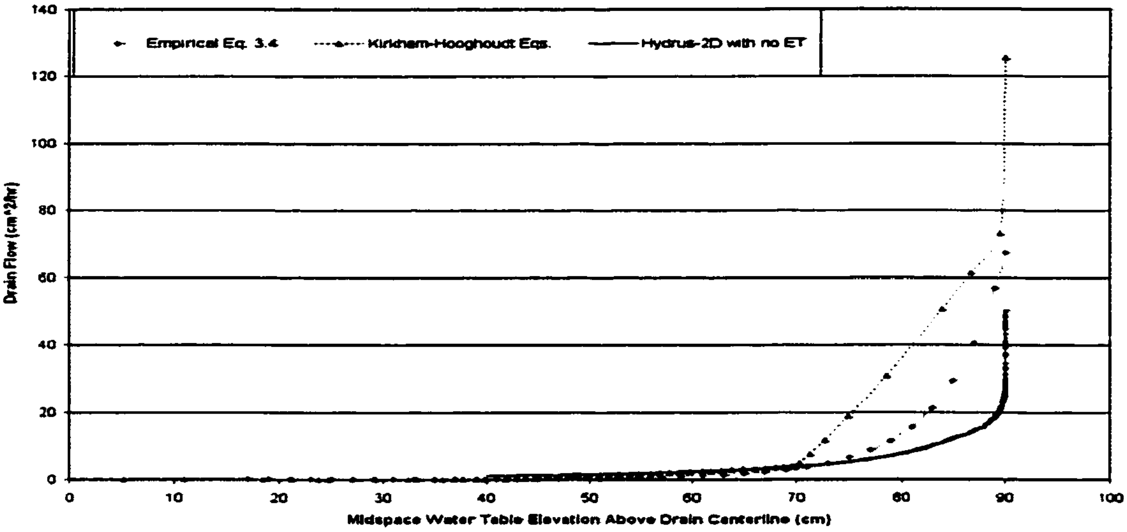

Figure 3.9. Drain flow-water table elevation relationship using HYDRUS-2D with all backfill K_{sat} values equal to 2.54 cm/hr (1 in/hr), and with no ET compared to those using the empirical Equation 3.4 and the Kirkham-Hooghoudt equations for Toledo silty clay soil.

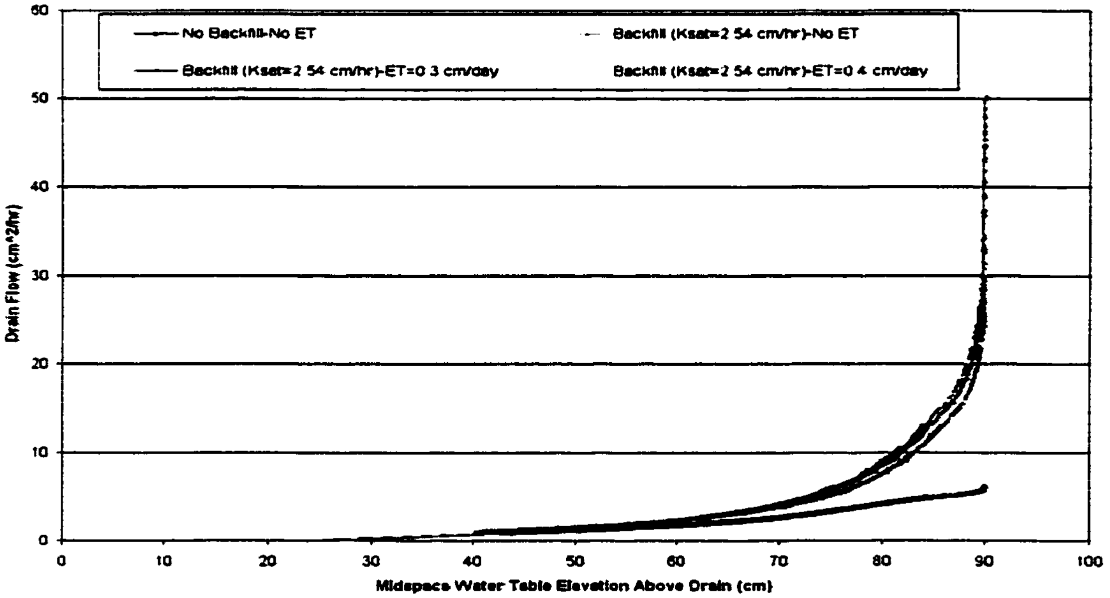

Figure 3.10. Drain flow-water table elevation relationship using HYDRUS-2D for the cases: 1) without backfill and with no ET (bottom curve); 2) with all backfill K_{sat} values equal to 2.54 cm/hr, and with no ET; 3) with all backfill K_{sat} values equal to 2.54 cm/hr (1 in/hr), and with a ET rate of 0.3 cm/day; and 4) with all backfill K_{sat} values equal to 2.54 cm/hr (1 in/hr), and with a ET rate of 0.4 cm/day (top curve).

It is clear from Figures 3.5, 3.8, and 3.9 that as the physical system is better defined in HYDRUS-2D, its predictions of drain flow begin to match those of Equation 3.4 as well or better than those from the Kirkham-Hooghoudt equations.

To further quantify this point, predictions of drain flow using the Kirkham-Hooghoudt equations and HYDRUS-2D were computed for a range of water table elevations between 40 and 90 cm (15.7 and 35.4 in), and compared to those of Equation 3.4. These results are presented in Figure 3.11 for the case where there is no ET from HYDRUS-2D. As mentioned before, conceptually, drain flows computed using Equation 3.4 were considered as the best fit to drain flow data.

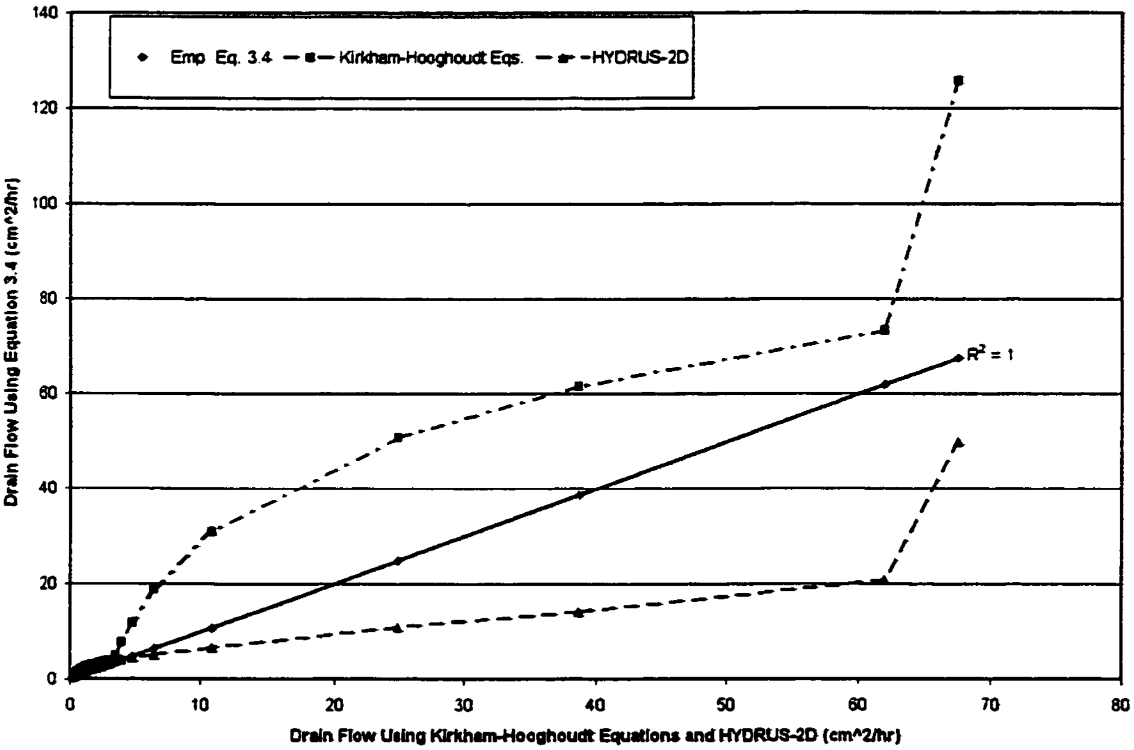

Figure 3.11. Relationships between drain flows predicted using Equation 3.4 and the drain flows predicted using the Kirkham-Hooghoudt equations and HYDRUS-2D (with no ET).

The specific objective of this part of the research was to simulate drain flow into subsurface drainage pipes for a layered soil profile using HYDRUS-2D (Simunek et al., 1996). Within the scope of the analyses presented above and the available data, objective 1 was met as discussed above. Figures 3.5, 3.8, and 3.9 illustrate the capability of using HYDRUS-2D to predict drain flows. No specific limitations in model capability were found. However, there were limitations in model application because of the lack of appropriate measured input data.

3.4.2 Objective 2: Develop a New Drain Flow Equation for Transition Conditions of Water Table for a Layered Soil

The drain flow results presented above show that the HYDRUS-2D model can be used to predict drain flows, at least within the scope of the available input data. To develop a new equation similar to 3.1 (by Salem and Skaggs, 1998) for layered soils, a key result must have been met. Equation 3.1 was developed by fitting SWMS-2D drain flow results especially for transitional water table conditions that occur between the conditions the Kirkham equation models and conditions that the Hooghoudt equation models (see Appendix I, Figure 2).

In the work by Salem and Skaggs (1998), SWMS-2D provided similar drain flows to those using the Hooghoudt equation for water table elevations up to those where transitional conditions begin. Also, SWMS-2D provided similar drain flows to those using the Kirkham equation for water table elevation that normally are covered by the Kirkham equation (i.e., water table at the surface and water ponded). Overall, SWMS-2D calculates the same drain flow rates that occur during the transition between the conditions that are modeled well with the Kirkham and Hooghoudt equations individually. At the end points of transition, the same drain flow values are estimated by SWMS-2D and the Kirkham equation, and SWMS-2D and the Hooghoudt equation.

For the current research, for a layered soil with using HYDRUS-2D (windows version of SWMS-2D), modeling the transitional conditions between those covered by the Kirkham equation and those by the Hooghoudt equation, and therefore producing the same drain flow values at the endpoints of the transition water table condition was not accomplished, at least at both endpoints. Based upon the results for objective 1, the HYDRUS-2D drain flow predictions matched those produced using the Hooghoudt equation at the transition point approximately of 70 cm water table elevation. However, at the upper end of the transition (approximately 90 cm), HYDRUS-2D was not able to produce the same drain flow rates as produced by the Kirkham equation. However, when input data values were assumed for backfill K_{sat} that help reduce the apparent restriction of water flow between the top layers and the drain tube, the HYDRUS-2D predictions at the upper endpoint of the transition were improved. This result warrants further evaluation that is now beyond the scope of this study.

3.5 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The specific objectives of the work presented in this chapter were: 1) to simulate drain flow into subsurface drainage pipes for a layered soil profile using HYDRUS-2D (Simunek et al., 1996); and 2) to develop an equation similar to that developed by Salem and Skaggs (1998) to predict drain flow rates for transition conditions of water table for a layered soil. Data from the drainage experiment of Schwab et al. (1963; 1975; and 1985) at the Ohio Agricultural Research and Development Center (OARDC) North Central Branch, near Sandusky, Ohio, was used as input to the model. Drain flow and corresponding water table depth data from 1960-1962 were used. In addition, saturated hydraulic conductivity (K_{sat}) values from the core data of Schwab et al. (1963) were used.

The HYDRUS-2D model was used to develop drain flow-water table elevation curves to be compared to the following: i) drain flow-water table relationship described by Hoffman (1963) as the best empirical relationship for the measured drain flow and corresponding midspace water table elevation data from the OARDC site; and ii) the relationship described using the Kirkham and Hooghoudt equations. For this analysis, the drain was represented as a completely permeable half circle with radius equal to the effective radius of the drain. To prevent water entry into the profile from the drain, the boundary represented by the drain was considered as a seepage face with pressure head equal to zero at the beginning of the simulation.

The results for the work conducted under each objective are summarized below with conclusions and recommendations relative to each objective.

3.5.1 Objective 1: Simulating Drain Flow with HYDRUS-2D

This component of the research was conducted to help determine the ability of the model to predict drain flow-water table elevation relationships and considered two cases of water loss at the soil surface: with evapotranspiration and with no evapotranspiration. The model was then used to evaluate the effect of backfill on drain flow-water table depth relationships with and without evapotranspiration.

HYDRUS-2D underpredicted drain flow compared to the empirical and the Kirkham-Hooghoudt equations for water table elevations above 70 cm (27.5 in). However, HYDRUS-2D predictions were very close to those using empirical and the Kirkham-Hooghoudt equations for water table elevations below 70 cm. There was no difference in the HYDRUS-2D curves for the cases where ET = 0 and for an ET rate of 0.3 cm/day.

There was little difference between the HYDRUS-2D curves for the no backfill simulation and for the backfill simulation used with backfill soil K_{sat} values obtained forty years after installation of the drains at the site. In the backfill simulation scenario, the model produced slightly higher drain flow rates than those obtained without simulating backfill when the midspace water table elevation was greater than 70 cm (27.5 in), but still underpredicted drain flow compared to the empirical and the Kirkham-Hooghoudt equations. To better reflect conductivity values for the backfill in 1960-1962, a range of saturated hydraulic conductivity values within the limits of the undisturbed soil core K_{sat} values (Schwab et al., 1963) were assigned to the backfill layers. The best HYDRUS-2D results were obtained when a value of 2.54 cm/hr (1 in/hr) was used for all backfill layers. The resulting curve showed substantial improvement in drain flow predictions from HYDRUS-2D especially when the water table elevation was greater than 70 cm. In the range of water table elevations from 70 to 90, the Kirkham-Hooghoudt equations over predict drain flow by approximately 82% and HYDRUS-2D underpredicts by 52%.

Within the scope of the analyses presented above and the available data, objective 1 was met as discussed above. Drain flow-water table elevation curves from HYDRUS illustrated the capability of using HYDRUS-2D to predict drain flows. No specific limitations in model capability were found. However, there were limitations in model application because of the lack of appropriate measured input data. The drain flow results showed that the HYDRUS-2D model can be used to predict drain flows, at least within the scope of the available input data. Further analysis using backfill K_{sat} values greater than 2.54 cm/hr (1 in/hr) can be performed.

3.5.2 Objective 2: Develop a New Drain Flow Equation for Transition Conditions of Water Table for a Layered Soil

To develop a new equation similar to that developed by Salem and Skaggs, (1998) for layered soils, a key result must have been met. The equation by Salem and Skaggs was developed by fitting SWMS-2D (Simunek et al., 1994) drain flow results especially for transitional water table conditions that occur between the endpoint conditions that the Kirkham equation models, and the endpoint condition that the Hooghoudt equation models.

Modeling the transitional conditions between those covered by the Kirkham equation and those by the Hooghoudt equation for a layered soil did not produce the same drain flow values at one endpoint of the transition as was accomplished by Salem and Skaggs (1998). At the lower end of transition (approximately 70 cm; 27.5 in), HYDRUS-2D was able to produce the same drain flow rate as produced by the Hooghoudt equation. However, at the upper end of the transition (approximately 90 cm; 35.4 in), HYDRUS-2D was not able to produce the same drain flow rates as produced by the Kirkham equation. At this point in the research, an equation similar to that of Salem and Skaggs could not be developed. Further research is recommended, however. This research needs to be conducted using input data from a subsurface drainage experiment site at which drain flows, midspace water table elevations, and saturated hydraulic conductivity values both in the original soil and the backfill are measured at the same time.

Before starting to develop WEPP-WTM model, it was realized that drain flow and water table depth prediction accuracy of WEPP hillslope model (Lane and Nearing, 1989) were not tested against field measured data. The next chapter covers this testing study.

3.6 REFERENCES

Baumer, Otto W. 1989. Predicting unsaturated hydraulic parameters. p.341:354. In M. Th. van Genuchten and F.J. Leij, and L.J. Lund (Eds.) Proceedings of the international workshop on indirect methods for estimating the hydraulic properties of unsaturated soils. Riverside, California, October 11-13. U.S. Dept. of Agriculture: Dept. of Soil and Environmental Sciences, University of California, c1992. 718 p.

Belmans, C., J.G. Wesseling and R.A. Feddes. 1983. Simulation model of the water balance of a cropped soil: SWATRE. J. Hydrology 63(1983):271-286.

Chung, S.O., A.D. Ward and C.W. Schalk. 1992. Evaluation of the hydrologic component of the ADAPT water table management model. Transactions of the ASAE 35(2):571-579.

Ernst, L.F. 1962. Grondwaterstromingen in de verzadigde zone en hun berekening bij aanwezigheid van horizontale evenwijdige open leidingen. Versl. Landbouwk. Onderz. 67-15. Pudoc, Wageningen. 189 p.

Fausey, N.R. 1975. Numerical model analysis and field study of shallow subsurface drainage. Ph.D. Thesis. Ohio State University, Columbus, Ohio. 147 p.

Fausey, N.R. 1977. Flow to shallow drain tubes in layered soils. 58-60. In Proc. of the 3'rd International Drainage Symposium. ASAE. 149 p.

Fipps, G., R.W. Skaggs and J.L. Nieber. 1986. Drains as a boundary condition in finite elements. Water Resource Research 22(11):1613-1621.

Hammad, H.Y. 1962. Depth and spacing of tile drain systems. ASCE Proceedings 88(IR1):15-34.

Hoffman, G.J. 1963. Tile flow from a stratified anisotropic soil with a falling water table. Master Thesis. Ohio State University, Columbus, Ohio. 83 p.

Hooghoudt, S.B. 1940. Algemeene beschouwing van het probleem van de detailontwatering en de infiltratie door middel van parallel loopende drains, greppels, slooteen, en kanalen. Versl. Landbouwk. Onderz. 46(14)B. Algemeene Landsdrukkerij, 's-Gravenhage, 193 p.

Kaluarachchi, J.J. and J.C. Parker. 1987. Finite element analysis of water flow in variably saturated soil. J. Hydrology 90(1987):269-291.

Kirkham, D. 1957. II. Theory of land drainage, III. The ponded water case. p:139-181. In J. N. Luthin (Ed.). Drainage of Agricultural Lands. Agronomy Monograph No. 7, American Society of Agronomy, Madison, Wisconsin. 620 p.

Klute, A. and C. Dirksen. 1986. Hydraulic conductivity and diffusivity: Laboratory methods. p:687-732. In A. Klute (Ed.). Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods. SSSA Book Series: 5 (formerly Agronomy Monograph 9). Madison, Wisconsin. 1188 p.

Lane, L.J. and M.A. Nearing (Eds.). 1989. USDA-Water erosion prediction project: Hillslope profile model documentation. NSERL Rep. No. 2, USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, Indiana. 265 p.

Martinez, M.A., E.J. Monke and E.J. Kladivko. 1989. Drain flow simulation using finite element technique. ASAE Paper No. 89-2099. St. Joseph, Mich.: ASAE. 19 p.

Merva, G.E., L. Segerlind, H. Murase and N.R. Fausey. 1983. Finite element modeling for depth and spacing of drains in layered soils. Transactions of the ASAE 26(2):452-456.

Pickens, J.F., R.W. Gillham and D.R. Cameron. 1979. Finite element analysis of the transport of water and solutes in tile-drained soils. J. Hydrology 40(1979):243-264.

Reyes, M.R., R.L. Bengston and J.L. Fouss. 1994. GLEAMS-WT hydrology submodel modified to include subsurface drainage. Transactions of the ASAE 37(4):1115-1120.

Richards, L.A. 1931. Capillary conduction of liquids through porous mediums. Physics 1(1):318-333.

Rogers, J.S. and J.L. Fouss. 1989. Hydraulic conductivity determination from vertical and horizontal drains in layered soil profiles. Transactions of the ASAE 32(2):589-595.

Rogers, J.S., H.M. Selim and J.L. Fouss. 1995. Comparison of drainage under steady rainfall versus falling water table conditions. Soil Science 160(6):391-399.

Sabbagh, G.J., J.L. Fouss and R.L. Bengston. 1993. Comparison of EPIC-WT and DRAINMOD simulated performance of land drainage system. Transactions of the ASAE 36(1):73-79.

Salem, H.E. and R.W. Skaggs. 1998. Predicting drainage rates under varying water table conditions. 168-175. In Proc. of the 7'th International Drainage Symposium. ed. L.C. Brown. ASAE. 738 p.

Schwab, G.O., T.J. Thiel, G.S. Taylor and J.L. Fouss. 1963.Tile and surface drainage of clay soils. Research Bulletin 935, Departments of Agricultural Engineering and Agronomy, Ohio Agricultural Experiment Station Wooster, Ohio. 47 p.

Schwab, G.O., N.R. Fausey and C.R. Weaver. 1975. Tile and surface drainage of clay soils. Research Bulletin 1081. Ohio Agricultural Research and Development Center, Wooster, Ohio. 37 p.

Schwab, G.O., N.R. Fausey, E.D. Desmond and J.R. Holman. 1985. Tile and surface drainage of clay soils. Research Bulletin 1166, Ohio Agricultural Research and Development Center, Wooster, Ohio. 29 p.

Segerlind, L.J. 1976. Applied Finite Element Analysis. John Wiley & Sons, NY. 422 p.

Simunek, J., T. Vogel and M. Th. van Genuchten. 1994. The SWMS_2D Code for Simulating Water Flow and Solute Transport in Two –Dimensional Variably Saturated Media. Ver. 1.21. Research Report No. 132. U.S. Salinity Laboratory, Agricultural Research Service, USDA, Riverside, California. 197 p.

Simunek, J., M. Sejna and M. Th. van Genuchten. 1996. Ground water modeling software HYDRUS-2D. Simulating water flow and solute transport in two-dimensional variably saturated media. IGWMC-TPS 53. Ver. 1.0 U.S. Salinity Laboratory, Agricultural Research Service, USDA, Riverside, California. 167 p.

Simunek, J. 1998. Personal communication. U.S. Salinity Laboratory, Agricultural Research Service, USDA, Riverside, California.

Skaggs, R.W. 1978. A water management model for shallow water table soils. Report No. 134. Raleigh, North Carolina. Water Resources Research Institute, Univ. of North Carolina. 175 p.

Skaggs, R.W. 1980. DRAINMOD Reference Report. Methods for design and evaluation of drainage-water management systems for soils with high water tables. North Carolina State University, Raleigh, North Carolina. 177 p.

Skaggs, R.W., N.R. Fausey and B.H. Nolte. 1981. Water management model evaluation for North Central Ohio. Transactions of the ASAE 24(4):922-928.

Smith, M.C., R.W. Skaggs and J.E. Parsons. 1985. Subirrigation system control for water use efficiency. Transactions of the ASAE 28(2):489-496.

Taylor, G.S., E. Stibbe, T.J. Thiel and J.H. Jones. 1970. Hydraulic conductivity profiles of Toledo and Miami Soils as measured by field monoliths. Research Bulletin. 1025. Ohio Agricultural Research and Development Center, Wooster, Ohio. 17 p.

Taylor, G.S. and N.R. Fausey. 1982. Backfill alterations and drainage of clay soils. 139-148. In Proc. of the 4'th International Drainage Symposium. ed. G.J. Kriz. ASAE. 177 p.

Trafford, B.D. and D.W. Rycroft. 1974. The natural soil as trench backfill. Technical Bulletin: 74/9, Ministry of Agriculture, Fisheries and Food, England. 9 p.

Van Genuchten. M.Th., F.J. Leij and S.R. Yates. 1991. The RETC code for quantifying the hydraulic functions of unsaturated soils, version 1.0. EPA Report 600/2-91/065. U.S. Salinity Laboratory, Agricultural Research Service, USDA, Riverside, California. 85 p.

Van Schilfgaarde, J. 1963. Design of tile drainage for falling water tables. J. Irrigation and Drainage Engineering ASCE 89(IR2):1-11.

Vimoke, B.S. and G.S. Taylor. 1962. Simulating water flow in soil with an electric resistance network. Agr. Res. Serv. 41-65, USDA. 51 p.

Vimoke, B.S., T.D. Tyra, T.J. Thiel and G.S. Taylor. 1963. Improvements in construction and use of resistance networks for studying drainage problems. Soil Science Society of American J. 26(2):203-207.

Workman, S.R., R.W. Skaggs, J.E. Parsons and J. Rice (Eds). 1986. DRAINMOD User's Manual. Biological and Agricultural Engineering Department, North Carolina State University, Raleigh, North Carolina. 90 p.

Workman, S.R. and R.W. Skaggs. 1990. PREFLO: A water management model capable of simulating preferential flow. Transactions of the ASAE 33(6):1939-1948.

Yu S.C. and K.D. Konyha. 1992. Boundary modelling of steady saturated flow to drain tubes. 305-313. In Proc. of the 6'th International Drainage Symposium. ASAE. 501 p.

CHAPTER 4

EVALUATION OF THE HYDROLOGY COMPONENT OF THE WEPP HILLSLOPE MODEL FOR SUBSURFACE DRAINED CROPLAND

4.1 INTRODUCTION

The Water Erosion Prediction Project (WEPP) (Ascough II et al., 1997; Baffaut et al., 1997; Flanagan and Livingston, 1995; Flanagan and Nearing, 1995; Lane and Nearing, 1989; Nearing et al, 1989; and Liu et al., 1997) is a new continuous simulation erosion model with hillslope and watershed applications. Flanagan and Livingston (1995) stated that the hillslope routines are used on overland parts of the watershed and the watershed routines are used on channels and impoundments. A watershed is defined as one or more hillslopes draining into one or more channels and/or impoundments. Runoff characteristics, soil loss and deposition are first calculated on each hillslope. These results are saved in a pass file that is used during the watershed routing. Then the model combines the results from each hillslope and performs runoff and sediment routing through the channels and impoundments each time runoff is predicted on one of the hillslopes or channels. Various components of WEPP have been studied and evaluated (Nearing et al., 1989; Deer-Ascough et al., 1995; and Zhang et al., 1996).

The hillslope version of WEPP requires four major input data files: weather, soil, management, and slope. The weather file contains daily temperature (min., max., and dew point), precipitation, solar radiation, and wind speed and direction. The precipitation data can be entered in either of two formats: daily total rainfall with duration and ratios of time to rainfall peak/rainfall duration and maximum rainfall intensity/average rainfall intensity; and breakpoint data with cumulative time from the beginning of the storm in the first column and cumulative rainfall in the second column. The soil file includes the number of soil layers, texture, albedo, initial saturation, erodibility, critical shear, and effective hydraulic conductivity. The information required for each soil layer includes layer depth, cation exchange capacity, and sand, clay, organic matter, and rock percentages. The management file contains input data about field operations and dates, plant parameters, tillage sequence and implement parameters, plant and residue management, initial conditions, contouring, subsurface drainage, and crop rotations. The data required in the slope file are orientation, length, and steepness at points along the profile.

The hydrology routines of the model compute infiltration, runoff, evaporation, transpiration, soil water percolation, plant and residue interception of rainfall, depressional storage, and soil profile drainage by subsurface drains (Flanagan and Livingston, 1995). The water balance routines are a modification of the SWRRB model (Williams et al., 1985). The WEPP model uses the following water balance equation:

$$\Theta = \Theta_{in} + (P - I) \mp S - Q - ET - D - Q_d \quad \text{.......} 4.1$$

Where: Θ is the soil water content (m); Θ_{in} is the initial soil water in the root zone (m); P is the cumulative precipitation (m); I is the precipitation intercepted by plants (m); S is the water content of snow (m); Q is the runoff (m); ET is the evapotranspiration (m); D is the percolation loss below the root zone (m); and Q_d is the subsurface lateral flow or flow to subsurface drains (m) (Savabi and Williams, 1995). Runoff in the WEPP model is computed using the kinematic wave equations or an approximation to the kinematic wave solutions.

To calculate drain flow, WEPP uses the Hooghoudt equation (Hooghoudt, 1940) as given below (Savabi et al., 1995):

$$Q = \frac{K_e(8d_eH + 4H^2)}{L^2} \quad \text{.......} 4.2$$

where: Q is the drain flow depth (cm/day); K_e is the equivalent saturated hydraulic conductivity (cm/day); H is the midspace water table elevation (cm) above the drain; L is the drain spacing (cm); and d_e is the equivalent depth from the drain to the impermeable layer (cm). By comparison, DRAINMOD (Skaggs, 1978) uses the Kirkham equation (Kirkham, 1957) in addition to the Hooghoudt equation to calculate subsurface drain flow. To calculate the effective depth (d_e) in the Hooghoudt equation (Eq. 4.2), WEPP uses the following equations (Savabi et al., 1995):

for $0 < d/L < 0.3$;

$$d_e = \frac{d}{1+\frac{d}{L}(\frac{8}{\pi}\ln(\frac{d}{r_e})-3.4)} \tag{4.3}$$

where: d_e is the equivalent depth from the drain to the impermeable layer (cm); d is the depth from the center of the drain to the impermeable layer (cm); L is the drain spacing (cm); and r_e is the effective radius of the drain tubes (cm);

for $d/L \geq 0.3$;

$$d_e = \frac{L\pi}{8(\ln(\frac{L}{r_e})-1.15} \tag{4.4}$$

Equations 4.3 and 4.4 (previously given in Chapter 2 as Equations 2.9 and 2.11, respectively) are also used in DRAINMOD, except with the parameter α in place of the constant value 3.4 in Equation 4.3 above. Skaggs (1980) stated that usually α could be approximated as equal to 3.4 with negligible error for design purposes.

The equivalent saturated hydraulic conductivity (K_e) value in the Hooghoudt equation (Eq. 4.2) is calculated using layer depth weighted baseline effective conductivity values (K_b) in place of the saturated hydraulic conductivity (K_{sat}) used in DRAINMOD. WEPP calculates a baseline effective conductivity (K_b) (mm/hr) using the following empirically derived equations (Alberts et al., 1995):

$$K_b = -0.265 + 0.0086(100xsand)^{1.8} + 11.46CEC^{-0.75} \tag{4.5}$$

for soils with a clay content $\leq$ 40%; and

$$K_b = 0.0066e^{\left[\frac{2.44}{clay}\right]} \tag{4.6}$$

for soils with a clay content > 40%. In Equations 4.5 and 4.6, the terms sand and clay are the fractions of sand and clay; and CEC (meq/100g) is the cation exchange capacity of the soil. These equations were derived based on the WEPP model optimization simulations using measured and curve number (fallow condition) runoff amounts (Alberts et al., 1995). Therefore, the parameter

K_b is based on runoff optimization. In WEPP, water table depth is calculated as unsaturated depth from the soil surface. Then, the midspace water table elevation for Equation 4.2 is calculated by substracting the estimated water table depth from the drain depth. The time step in WEPP when predicting ET, drain flow, water table depth, and percolation is 24 hours.

The accuracy of storm and peak runoff predictions of the hydrology component of the WEPP hillslope model have been evaluated by several researchers (i.e., Liu et al., 1997; Savabi, 1993; Savabi et al.; 1995; Zhang et al., 1996) using field measured data. However the drain flow and water table depth predictions of the model were not tested against field measured data. The effect of the water table depth on runoff and sediment yield was evaluated for a hypothetical site by Savabi et al. (1995). Their results are summarized in Appendix K (Figures 6.1.1 and 6.1.2).

The purpose of the work presented in this chapter is to gain some assessment of the hydrology component of WEPP for cropland with subsurface drainage. The specific objective is to evaluate the runoff, drain flow, and water table depth prediction accuracy of the WEPP hillslope model against the field measured runoff and drain flow data, and predicted water table depths from DRAINMOD. For the same simulation conditions, selected results from Chapter 2 will be presented here for comparison purposes.

4.2 MATERIALS AND METHODS

To evaluate the runoff, drain flow, and water table depth prediction accuracy of the WEPP hillslope model (Version 97.3), measured drain flow and runoff data were obtained from records from the drainage experiment of Schwab et al. (1963; 1975; and 1985) at the Ohio Agricultural Research and Development Center (OARDC) North Central Branch, near Sandusky, Ohio[1]. Specifically, data from plots that contained both surface and subsurface drainage improvements (combination plots) were chosen because of the availability of both runoff and drain flow measurements. There were no continuous water table depth measurements made on these plots. For this reason, water table depth predictions of WEPP will be compared to those using DRAINMOD. Sprinkler irrigation water was applied to the plots at the site twice each year in May, June, or July to provide a repeatable 10-year return period storm. The sprinkler irrigation system at the site covered two replications at one setting in 1969, 1970, and 1971. Selected WEPP simulation results were therefore compared to the mean of the two replications where the same rainfall and irrigation data were valid for both replications. A brief description of the North

---

[1] : The data from this site were also used to evaluate DRAINMOD for North Central Ohio conditions by Skaggs et al. (1981) and to evaluate the ADAPT model (Chung et al., 1992).

Central Branch drainage experiment and data collection at the site was given in Chapter 2 and will not be repeated here.

A preliminary evaluation showed that the drain flow and water table depth predictions of WEPP were poor. Therefore, in the following evaluations, WEPP runoff, drain flow, and water table depth prediction accuracy was evaluated for only three years (1969, 1970, and 1971) of North Central Branch data rather than the eight years used in Chapter 2.

Skaggs (1982) reported that DRAINMOD water table depth prediction was in excellent agreement with measured water table depths having standard errors ranging from 7.5 to 19.6 cm (2.9 to 7.7 in) for three sites in North Carolina. Based on the results reported in Chapter 2, the best drain flow and runoff predictions from DRAINMOD were obtained for the North Central Branch site using K_{sat} values estimated with the van Schilfgaarde equation (van Schilfgaarde, 1963) (Table 2.4 in Chapter 2) for Toledo silty clay. For the water table depth comparison, these DRAINMOD simulation results were used.

In this research, most of the drainage related inputs used in WEPP were the same as those used for the DRAINMOD simulations in Chapter 2. Additional input data were obtained from the experiment field notes, Fausey(1999), and selected published articles on research done at the site. The same daily maximum and minimum temperatures, and hourly rainfall data used in Chapter 2 with DRAINMOD were used with WEPP. Daily solar radiation, wind direction and speed, and dew point temperatures were obtained from the Midwestern Climate Data Center[2] (MCDC) for Toledo, Ohio, which is approximately 65 km (40.4 mi) west-north west from the OARDC North Central Branch site. The availability of daily solar radiation, temperature, and wind data allowed the use of the Penman equation with its original wind function (Jensen, 1974; Penman, 1963) to calculate reference potential evapotranspiration (ET). The combination plots at the site were surface drained at a 0.2% slope.

Soil input values for albedo, baseline interrill and rill erodibility, and critical shear were obtained using default equations given in the WEPP User Summary (Flanagan and Livingston, 1995). The same four soil layers used in the previous DRAINMOD simulations (Chapter 2) were used as input to WEPP, then the model internally created its own nine soil layers. Sand and clay contents of the soil layers were obtained from Schwab et al. (1963) (Appendix C, Table A1). Organic matter (OM) and cation exchange capacity (CEC) values were obtained using the MUUF (Map Unit Use File) soil database (Baumer, 1989). Table 4.1 lists these soil input data. The units for these parameters are those specified in the WEPP User Summary.

---

[2] : Illinois State Water Survey, 2204 Griffith Drive, Champaign, IL 61820-7495.

Albedo[*]:	0.1
Initial saturation level (%)[*]:	0.81
Baseline inter-rill erodibility (kgs/m^4)[*]:	3.24x10^6
Baseline rill erodibility (s/m)[*]:	0.0069
Baseline critical shear (N/m^2)[*]:	3.1
Baseline effective conductivity (mm/hr)[*]:	0.79

	Soil Layers			
	1	2	3	4
Depth from soil surface (cm)[#]:	20	50	102	165
Sand (%)[+]:	3	3	4	3
Clay (%)[+]:	51	53	55.7	57.3
OM (%)[+]:	4.5	1.5	1.5	1.5
CEC (meq/100 g soil)[*]:	35	31	29	28

*: These values were calculated using default equations given in the WEPP User Summary (Flanagan and Livingston, 1995). The soil data given by Schwab et al. (1963) (Appendix C, Table A1) were used in these equations.

#: Taken from Chapter 2, Table 2.4

+: Taken from Schwab et al. (1963) (Appendix C, Table A1)

Table 4.1. Soil input data used in the WEPP hillslope model for Toledo silty clay at the drainage experiment of the OARDC North Central Branch, near Sandusky, Ohio.

Plant parameters for corn were obtained from the WEPP validation input data set files[3]. Field operations and their dates were obtained from the experiment field notes. The drainage system parameters and values used in the drainage section of the WEPP management file were: drain depth = 90 cm (35.4 in); drainage coefficient = 5.3 cm/day[4] (2.1 in/day); drain diameter = 10 cm (4 in); and drain spacing = 12.2 m (40 ft).

Daily and cumulative runoff and drain flows simulated by WEPP were compared to the measured runoff and drain flows. As mentioned in Chapter 2, because of the starting date inconsistencies of outflow measurements made in March at the North Central Branch as stated by

---

[3] : The USDA-ARS National Soil Erosion Research Laboratory maintains a web site for WEPP. This site has a page called "Hillslope Validation Data" which contains parameter selection help and hydrology validation results. (http://topsoil.nserl.purdue.edu/weppmain/wepp.html).

[4] : This value was determined using the empirical Equation 2.12 (Chapter 2) developed by Hoffman (1963) after assuming the midspace water table elevation was a maximum at 90 cm (2.95 ft).

Skaggs et al. (1981), these evaluations were based on the measured data from April 1 to September 30 each year, 1969-1971. The agreement between predicted and measured values was quantified on the basis of daily and cumulative values for each evaluation year by computing average deviation (cm) as:

$$average\text{-}deviation = \sum_{i=1}^{n} \mid x_i - y_i \mid / n \ldots\ldots\ldots\ldots\ldots\ldots 4.7$$

where: x_i is the predicted daily drain flow or runoff volume; y_i is the measured daily drain flow or runoff volume on day i; and n=183, the number of days in the simulation period (April 1 to September 30). Equation 4.7 was also used to calculate the agreement between cumulative predicted and measured outflows. In this situation, starting from April 1 (i = 1), x_i is the predicted cumulative drain flow or runoff volume; and y_i is the measured cumulative drain flow or runoff volume on day i. When the WEPP predicted daily water table depths were compared to the DRAINMOD predicted water table depths, the agreement between these two models was quantified by calculating a standard error using the following equation:

$$s = \sqrt{\sum_{i=1}^{n} (Y_i - Y_i') / n} \ldots\ldots\ldots\ldots\ldots\ldots 4.8$$

where: s is the standard error (cm); n is the number of days (183) in the simulation period (April 1 to September 30); Y_i is the DRAINMOD predicted water table depth (cm); and $Y_i^{'}$ is the WEPP predicted water table depth (cm). For water table depths, the average deviation was also computed using Equation 4.7.

The WEPP hillslope model simulations calculate a daily midspace water table depth (unsaturated depth) and drain flow. However, they are not output to any user file. Therefore, variables for the midspace water table depth and drain flow were added to the source code of the WEPP hillslope model, and these variables were added to the water balance output file, where the daily predicted runoff depths are also output.

4.3 RESULTS AND DISCUSSION

WEPP hillslope model predicted baseline effective conductivity values (K_b) for nine soil layers are given in Table 4.2 along with the K_{sat} values derived in Chapter 2 using the van Schilfgaarde equation (van Schilfgaarde, 1963) and the MUUF soil database. Remember that when DRAINMOD was used with the van Schilfgaarde equation estimated K_{sat} values, the best drain flows and runoff predictions were obtained and when MUUF database K_{sat} values were used in DRAINMOD, the worst drain flows and runoff predictions were obtained in Chapter 2. The WEPP predicted conductivity values appear to be very low, almost 10 times lower than the MUUF saturated hydraulic conductivity values. The WEPP values are approximately 100 times smaller than the van Schilfgaarde equation estimated values down to the 50 cm (19.7 in) depth. For the layers below 50 cm, however, the WEPP values are relatively close to those from the van Schilfgaarde equation. At this point, it may be reasonable to say that WEPP will overpredict runoff and underpredict drain flow compared to the measured flows and DRAINMOD. If we ignore different hydraulic conductivity values usage (K_b vs. K_{sat}) in both WEPP and DRAINMOD and if we consider that both WEPP and DRAINMOD are using the same form of Hooghoudt equation to predict drain flow when midspace water table depth is less than 0.5 cm (0.2 in) from the soil surface, similar results would be expected from both models.

The calculated average deviation between the daily and cumulative measured and predicted drain flow and runoff depths are given in Table 4.3. The minimum average deviation value for each replication among the WEPP and DRAINMOD simulations is underlined. When we consider the mean of the average deviations for daily drain flows, the results obtained with the WEPP are 7.7-, 3.8-, and 4.8-times larger than those obtained with DRAINMOD using the van Schilfgaarde equation estimated K_{sat} values, and 3.2-, 2.2-, and 2.9-times larger than those obtained with DRAINMOD using the MUUF database K_{sat} values, for years 1969, 1970, and 1971, respectively. Drain flow simulation results with WEPP for all replicates of these three years produced the largest average deviation values.

For the mean of the average deviations for daily runoff, WEPP again produced 2.7-, 1.1-, and 3-times larger values than those obtained with DRAINMOD using the van Schilfgaarde equation estimated K_{sat} values, and 1.3-, 1.1-, and 3.2-times larger than those obtained with DRAINMOD using the MUUF database K_{sat} values, for years 1969, 1970, and 1971, respectively. All replicate average deviations obtained from WEPP are larger than those obtained from DRAINMOD using MUUF database K_{sat} values, and larger than those obtained from DRAINMOD using the van Schilfgaarde equation estimated K_{sat} values except replications 3 and 4 in 1970.

Layer Thickness$^+$ (cm)	Baseline Effective Conductivity (cm/hr)	Layer Thickness* (cm)	Saturated Hydraulic Conductivity van Schilfgaarde (cm/hr)	Saturated Hydraulic Conductivity MUUF Database (cm/hr)
10	0.0790	20	42.477	0.879
10	0.0790	30	1.920	0.336
20	0.0538	52	0.052	0.279
20	0.0461	63	0.010	0.279
20	0.0394			
20	0.0394			
20	0.0331			
20	0.0325			
20	0.0325			

$^+$: WEPP derived values

*: Values derived in Chapter 2 and then used with DRAINMOD for the same site

Table 4.2. Baseline effective conductivity values (K_b) predicted by the WEPP hillslope model using Equations 4.4 and 4.5 for the Toledo silty clay input data given in Table 4.1, and K_{sat} values from Chapter 2 (Table 2.4).

		Cumulative Outflows		Daily Outflows	
Year	Replication	Runoff	Drain flow	Runoff	Drain flow
1969	1	9.21	42.70	0.081	0.358
	2	9.08	45.43	0.080	0.360
	3	8.05	35.97	0.089	0.307
	4	4.67	32.29	0.104	0.307
	Average	7.75	39.10	0.088	0.333
1970	1	3.96	21.12	0.046	0.201
	2	3.46	23.77	0.042	0.213
	3	2.66	23.95	0.052	0.213
	4	1.16	23.15	0.069	0.222
	Average	2.81	23.00	0.052	0.212
1971	1	3.04	13.45	0.062	0.114
	2	2.58	14.46	0.061	0.122
	3	1.95	12.86	0.062	0.111
	4	1.67	13.66	0.058	0.112
	Average	2.31	13.61	0.061	0.115

Table 4.3. Average deviations (cm) between daily and cumulative predicted and observed drain flows and runoff. The observed values were obtained from the drainage experiment of OARDC North Central Branch, Near Sandusky, Ohio (Schwab et al., 1963; 1975; and 1985).

For cumulative drain flows, WEPP produced 11.5-, 8.7-, and 16.7-times larger mean deviations than those obtained from DRAINMOD with van Schilfgaarde K_{sat}, and produced 5.6-, 11.7-, and 7-times larger mean deviations than those obtained from DRAINMOD with MUUF K_{sat}. Average deviation values for WEPP predicted cumulative drain flows for each replication are larger than those obtained from DRAINMOD. For cumulative runoff, WEPP produced 3.7- and 1.4-times larger values than those from DRAINMOD with van Schilfgaarde K_{sat}, and 1.1- and 2.3-times larger than those from DRAINMOD with MUUF K_{sat} for years 1969 and 1971, respectively. For 1970, the mean average deviation obtained from WEPP is 1.8-times less than that obtained with DRAINMOD with van Schilfgaarde K_{sat}, however, it is 1.1-times larger than that obtained from DRAINMOD with MUUF K_{sat}. Except for replications 3 and 4 in 1970, all replicate average deviations from WEPP are larger than those obtained from DRAINMOD.

Figures 4.1 through 4.3 illustrate daily drain flow predictions of WEPP hillslope model for the years 1969 through 1971, respectively, compared to the measured drain flows. The measured values shown are the average of the daily drain flows from one pair of the replicate combination plots (same rainfall and irrigation data). From these figures, it is clear that daily drain flows were overpredicted for all storm events except for day 79 in 1969. Furthermore, for all three years, large amounts of daily drain flows were predicted while there were little or no drain flows from the field, such as day 4, 63, and 84 (Figure 4.1). For 1970 (Figure 4.2), while there was a small amount of observed drain flow during days 111 and 121, WEPP did not predict any drain flow for these days.

Figures 4.4 through 4.6 illustrate daily runoff predictions from WEPP for the evaluation years. The predicted values are again compared to the mean of the measured runoff depths from the two individual replicates (same rainfall and irrigation data). For 1969 (Figure 4.4), WEPP predicted runoff on the same days on which runoff was measured, however, WEPP overpredicted runoff for these days, especially for days 48 and 79 (almost three times larger). The best WEPP runoff predictions were obtained for replicates 3 and 4 in 1970 (Figure 4.5). This prediction quality was not seen for replicates 1 and 2 during the same year (not shown). For 1971, WEPP again overpredicted runoff for three observed storm events (Figure 4.6). WEPP produced a 2.3 times larger runoff depth than the average observed runoff depth during day 72. Furthermore, a very large runoff depth was predicted on day 143, however there was no measured runoff on that day. It is interesting to note that DRAINMOD did predict runoff on this day, but the value was 95% smaller than that of WEPP (Chapter 2, Figure 2.5).

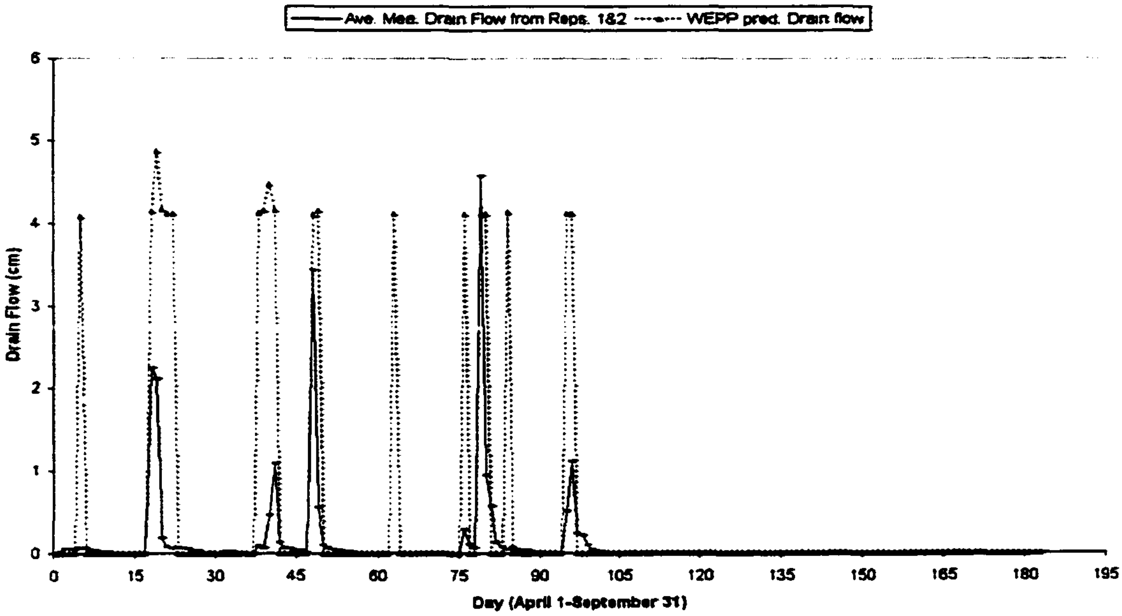

Figure 4.1. Daily WEPP predicted and average measured drain flow from replications of 1 and 2 during 1969 at the drainage experiment of OARDC North Central Branch, near Sandusky, Ohio (Schwab et al., 1963; 1975; and 1985).

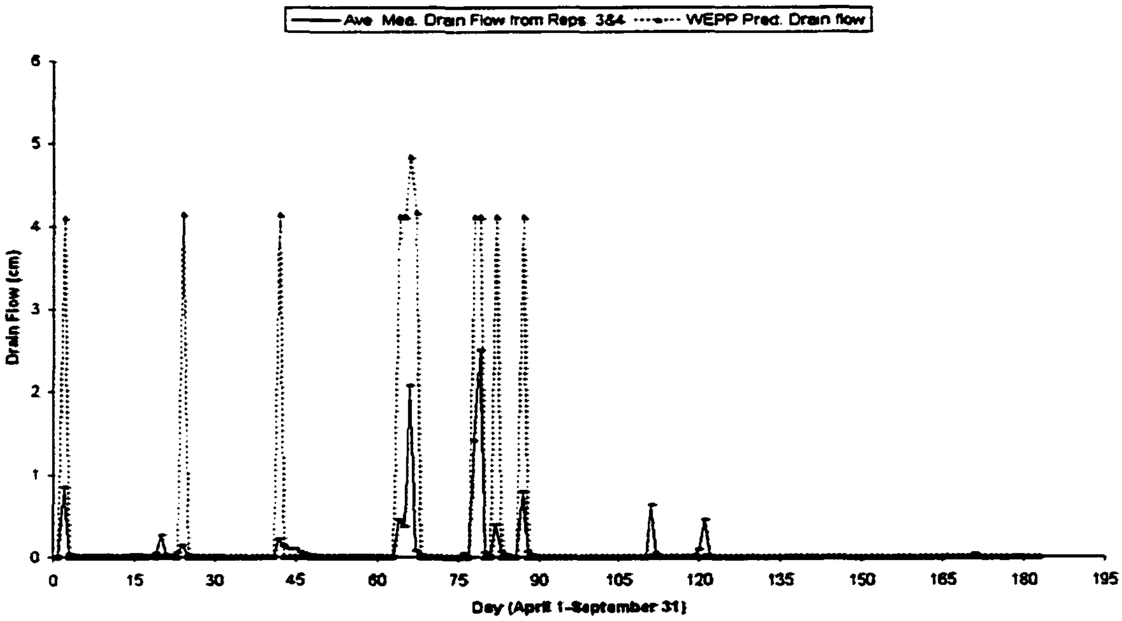

Figure 4.2. Daily WEPP predicted and average measured drain flow from replications of 3 and 4 during 1970 at the drainage experiment of OARDC North Central Branch, near Sandusky, Ohio (Schwab et al., 1963; 1975; and 1985).

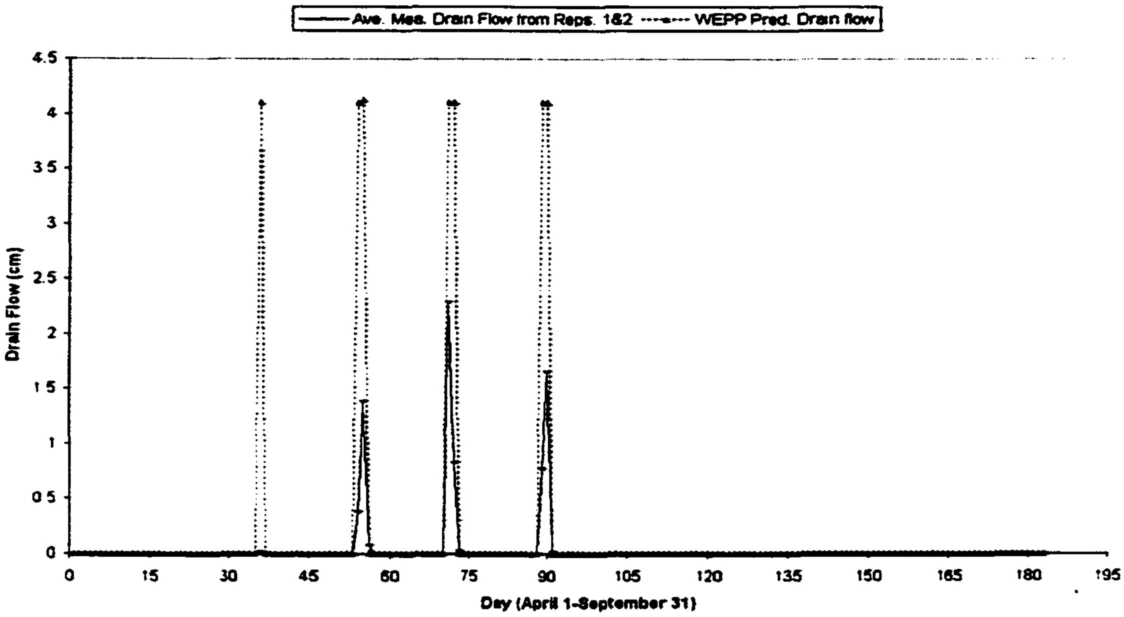

Figure 4.3. Daily WEPP predicted and average measured drain flow from replications of 1 and 2 during 1971 at the drainage experiment station of OARDC North Central Branch, near Sandusky, Ohio (Schwab et al., 1963; 1975; and 1985).

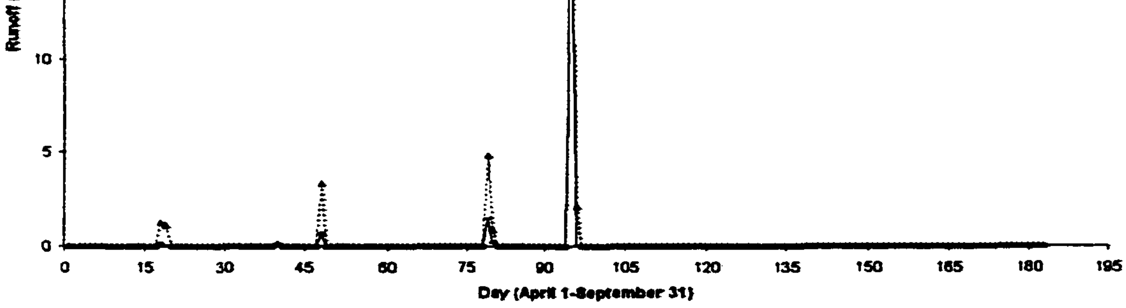

Figure 4.4. Daily WEPP predicted and average measured runoff from replications of 1 and 2 during 1969 at the drainage experiment of OARDC North Central Branch, near Sandusky, Ohio (Schwab et al., 1963; 1975; and 1985).

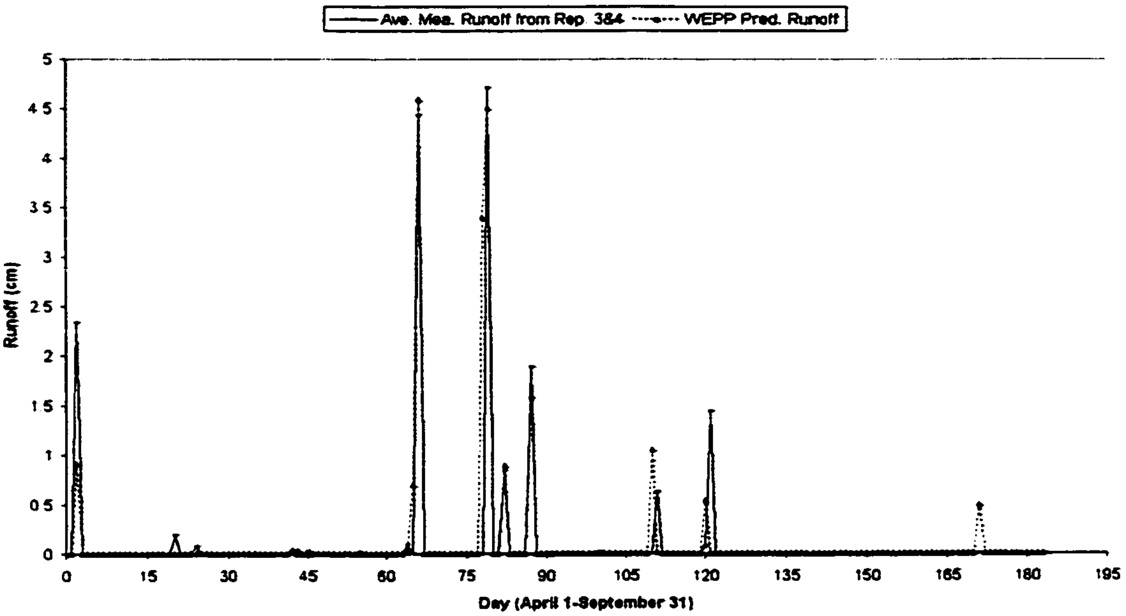

Figure 4.5. Daily WEPP predicted and average measured runoff from replications of 3 and 4 during 1970 at the drainage experiment of OARDC North Central Branch, near Sandusky, Ohio (Schwab et al., 1963; 1975; and 1985).

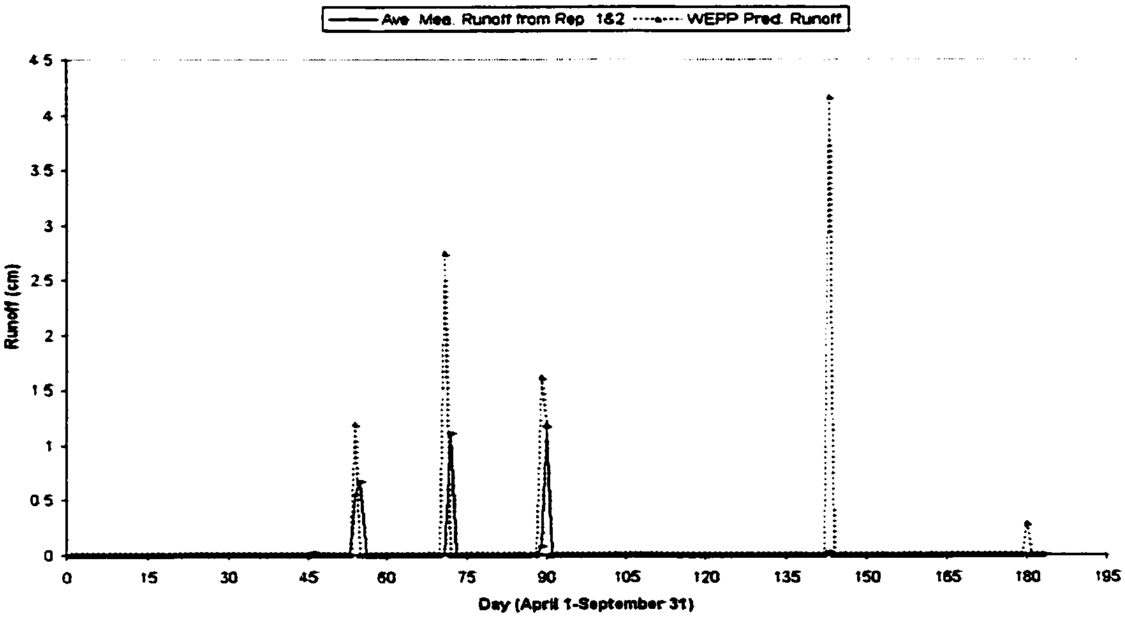

Figure 4.6. Daily WEPP predicted and average measured runoff from replications of 1 and 2 during 1971 at the drainage experiment of OARDC North Central Branch, near Sandusky, Ohio (Schwab et al., 1963; 1975; and 1985).

Figures 4.7 through 4.9, cumulative drain flows, illustrate again the differences between predicted and measured drain flows and how the cumulative drain flows correspond to the event based data shown in Figures 4.1 through 4.3. From these figures, it is apparent again that there are large differences between measured and predicted cumulative drain flows during the whole evaluation time period. The predicted cumulative drain flows at the end of evaluation season are almost four times larger than measured drain flows for all three years. At the end of evaluation season, the differences between predicted and average measured drain flows from the replicate pairs are 58.6, 33.8, and 21.3 cm (23.1, 13.3, and 8.4 in) in 1969, 1970, and 1971, respectively.

The cumulative runoff depths shown in Figures 4.10 through 4.12 illustrate again that the runoff was also overpredicted by WEPP. Figures 4.10 and 4.12 illustrate how poorly the predicted runoff depths correspond to the measured runoff depths from replications 1 and 2 for years 1969 and 1971, while Figure 4.10 illustrates how well the predicted runoff correspond to the measured runoff from replications 3 and 4 in 1970. At the end of evaluation season, the runoff depth differences between predicted and the average measured runoff depths of these replicate pairs are 14.7, 2.1, and 7.6 cm (5.8, 0.8, and 3.0 in) for the three years shown in Figures 4.10 through 4.12, respectively.

WEPP and DRAINMOD predicted water table depths are given in Figures 4.13 through 4.15. After analyzing the results, it is difficult to conclude that WEPP is even simulating water table depth. In WEPP, there is no continuous water table depth prediction. The water table moves to the surface from the bottom of the soil profile very quickly with only a small amount of rainfall. For a couple of the simulation days, the water table stays at the surface, then quickly returns to the bottom of the soil profile. In another words, the soil profile transitions between saturated and unsaturated conditions very quickly, which is unusual for a silty clay soil. The calculated standard errors and average deviations between WEPP and DRAINMOD predicted midspace water table depths are given in Table 4.4. The calculated standard errors and average deviations between WEPP and DRAINMOD predicted water table depths are very large, in the range of 0.5 to 0.75 m (1.64 to 2.46 ft).

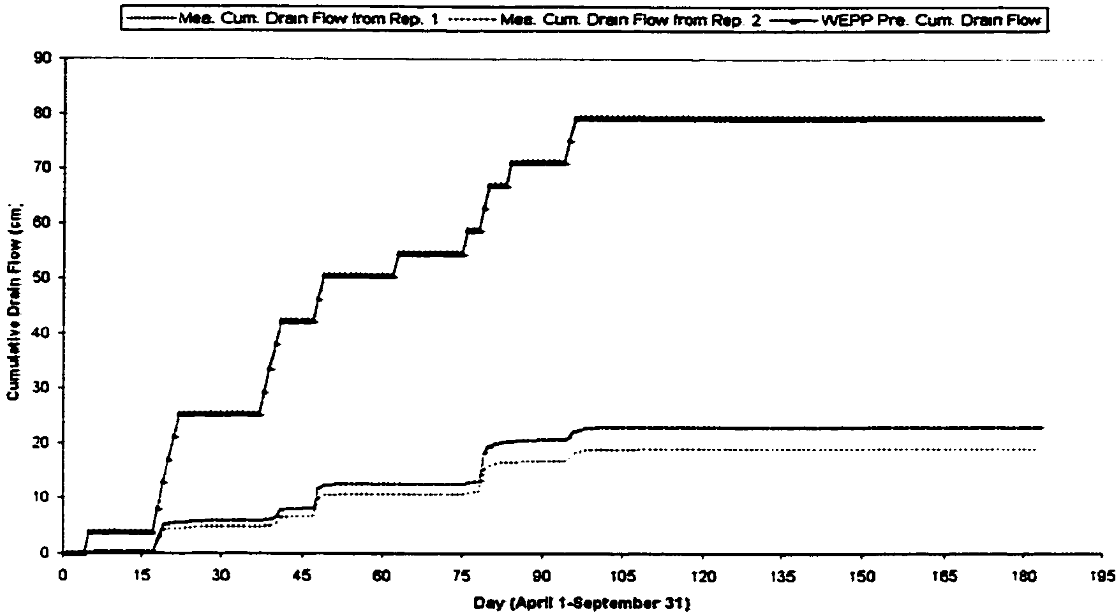

Figure 4.7. WEPP predicted and measured cumulative drain flows from replications of 1 and 2 during 1969 at the drainage experiment of OARDC North Central Branch, near Sandusky, Ohio (Schwab et al., 1963; 1975; and 1985).

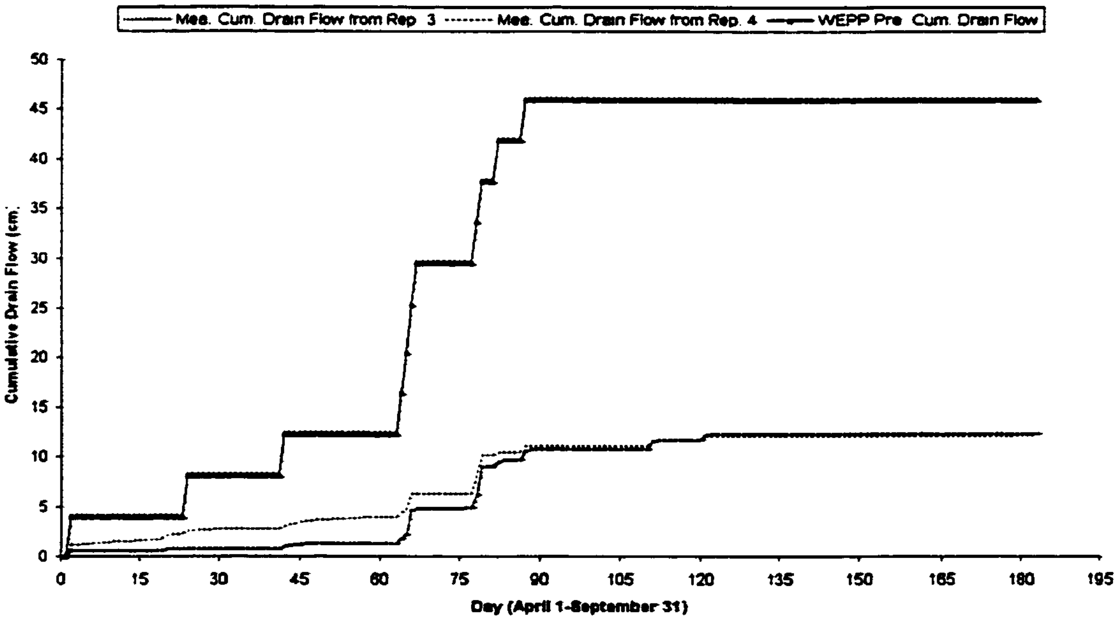

Figure 4.8. WEPP predicted and measured cumulative drain flow from replications of 3 and 4 during 1970 at the drainage experiment of OARDC North Central Branch, near Sandusky, Ohio (Schwab et al., 1963; 1975; and 1985).

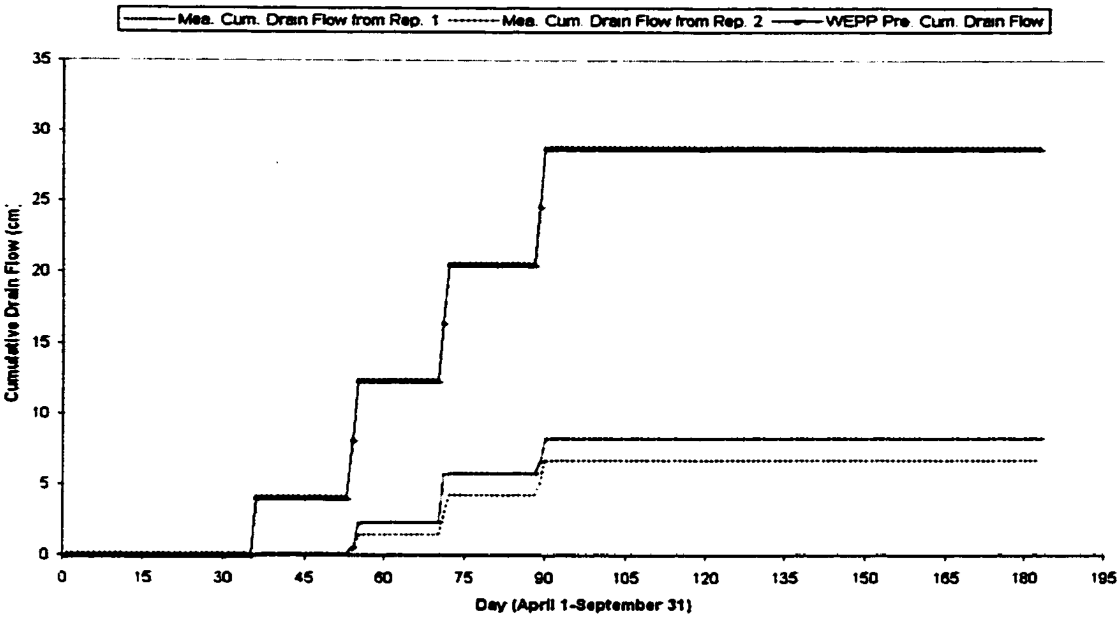

Figure 4.9. WEPP predicted and measured cumulative drain flow from replications of 1 and 2 during 1971 at the drainage experiment of OARDC North Central Branch, near Sandusky, Ohio (Schwab et al., 1963; 1975; and 1985).

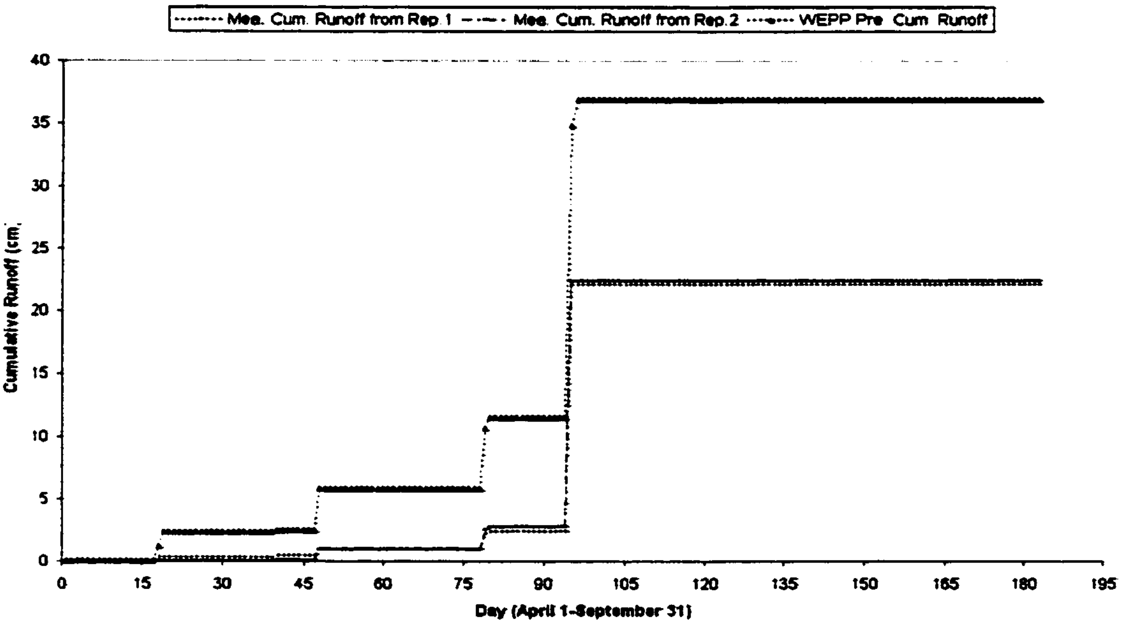

Figure 4.10. WEPP predicted and measured cumulative runoff from replications of 1 and 2 during 1969 at the drainage experiment of OARDC North Central Branch, near Sandusky, Ohio (Schwab et al., 1963; 1975; and 1985).

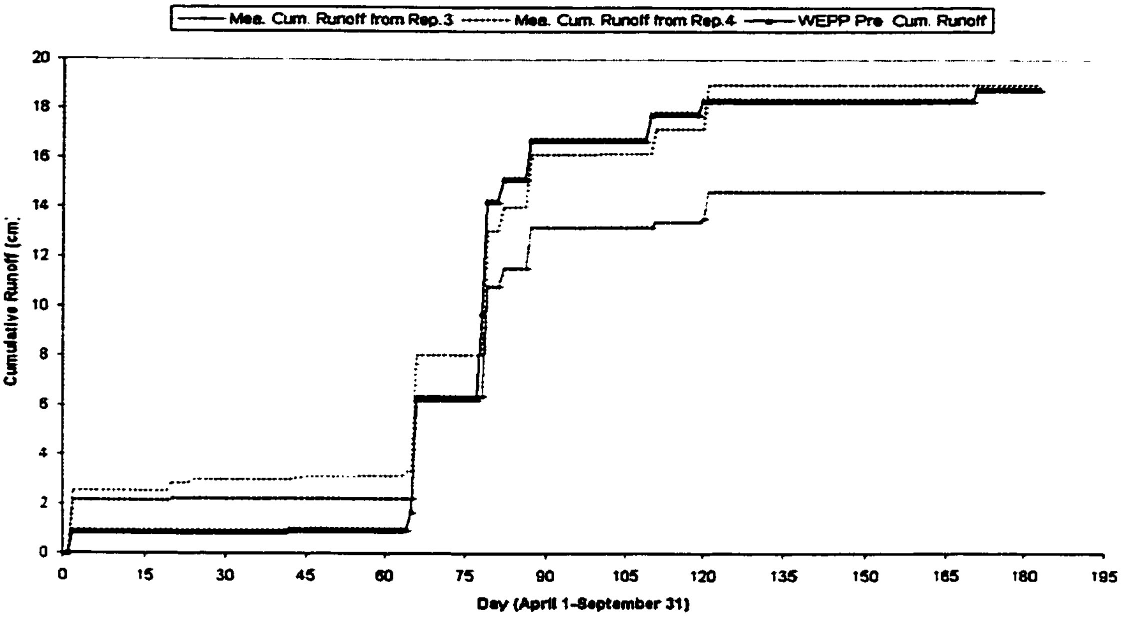

Figure 4.11. WEPP predicted and measured cumulative runoff from replications of 3 and 4 during 1970 at the drainage experiment of OARDC North Central Branch, near Sandusky, Ohio (Schwab et al., 1963; 1975; and 1985).

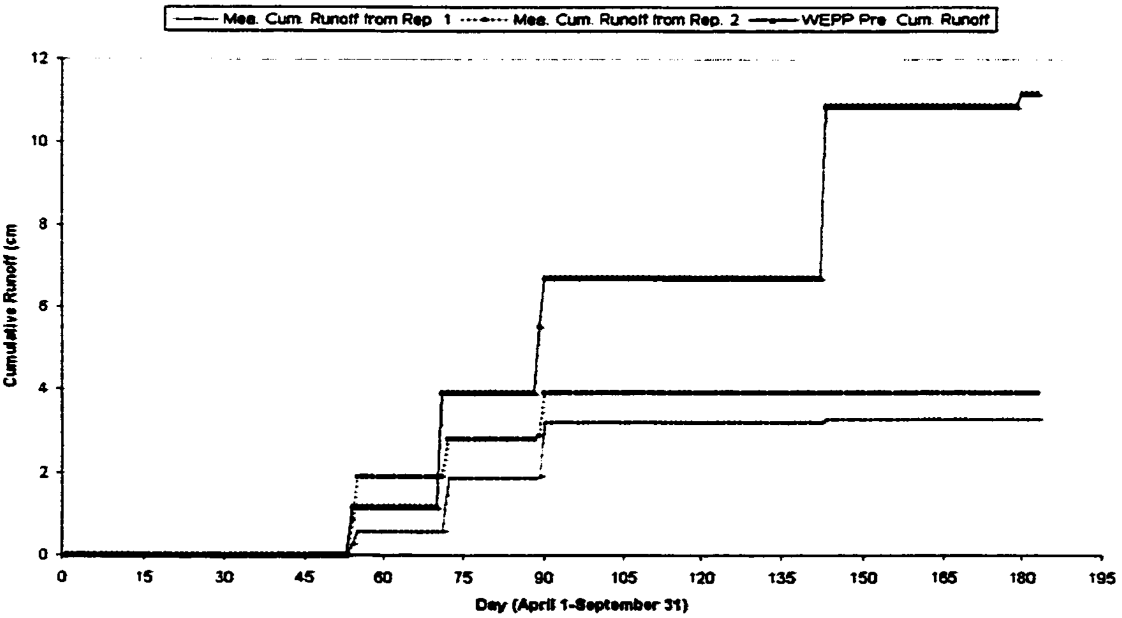

Figure 4.12. WEPP predicted and measured cumulative runoff from replications of 1 and 2 during 1971 at the drainage experiment of OARDC North Central Branch, near Sandusky, Ohio (Schwab et al., 1963; 1975; and 1985).

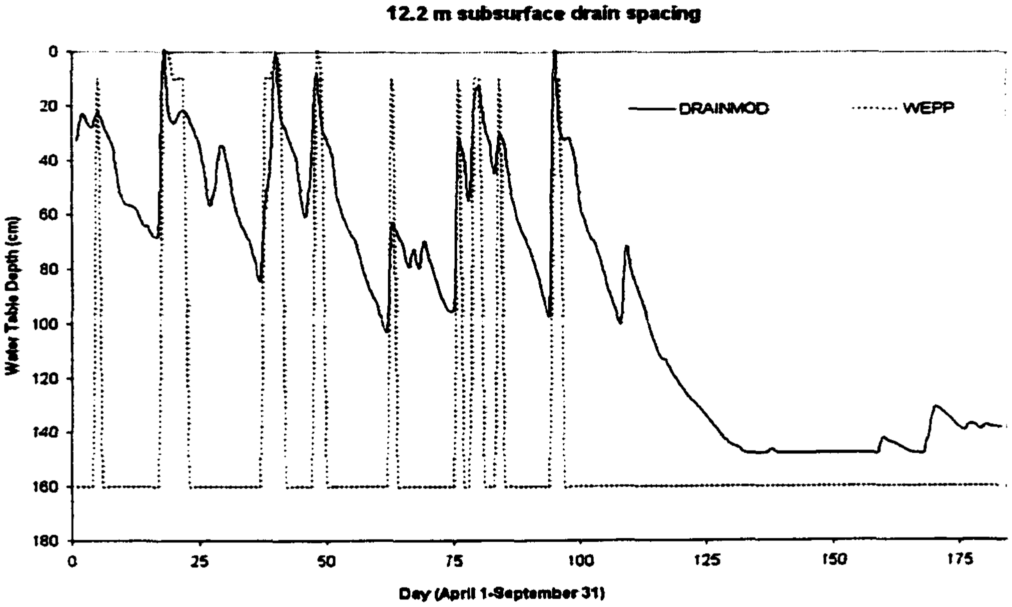

Figure 4.13. WEPP and DRAINMOD predicted midspace water table depths for the average of replications 1 and 2 during 1969 at the drainage experiment of OARDC North Central Branch, near Sandusky, Ohio (Schwab et al., 1963; 1975; and 1985).

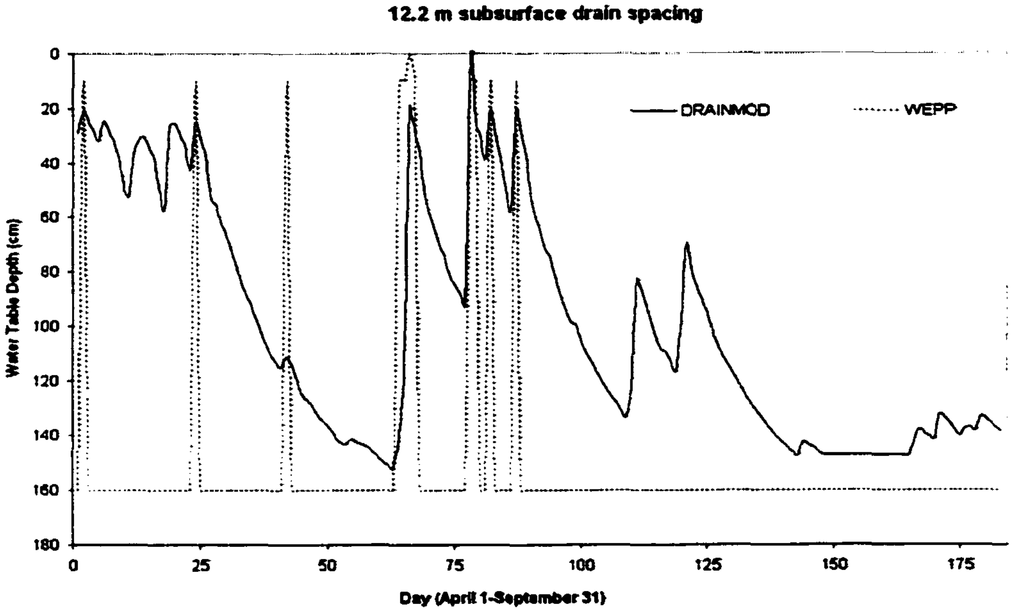

Figure 4.14. WEPP and DRAINMOD predicted midspace water table depths for the average of replications 3 and 4 during 1970 at the drainage experiment of OARDC North Central Branch, near Sandusky, Ohio (Schwab et al., 1963; 1975; and 1985).

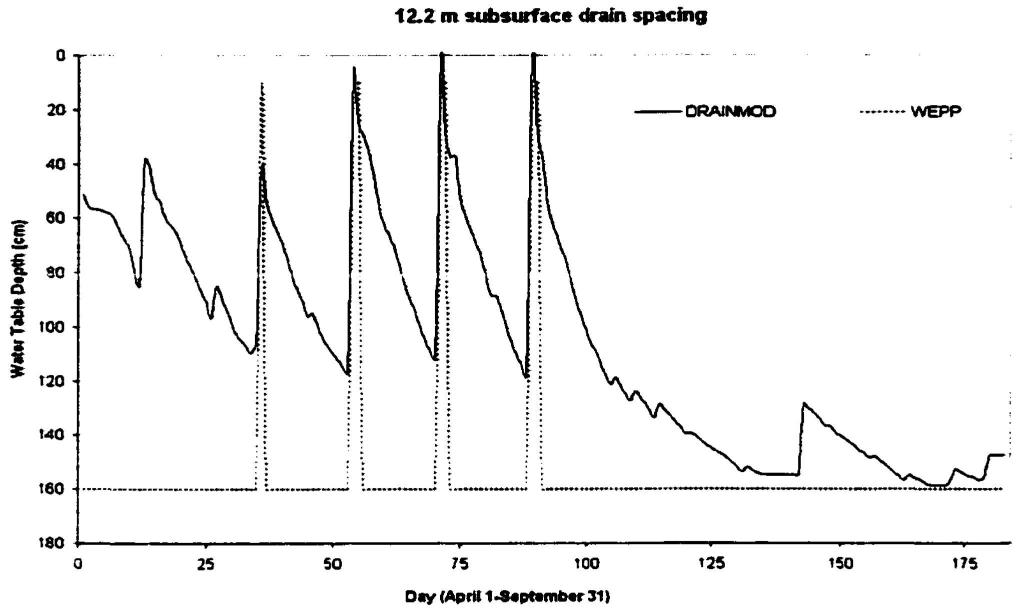

Figure 4.15. WEPP and DRAINMOD predicted midspace water table depths for the average of replications 1 and 2 during 1971 at the drainage experiment of OARDC North Central Branch, near Sandusky, Ohio (Schwab et al., 1963; 1975; and 1985).

Year	Replication	s (cm)	a.d.(cm)
1969	1&2	73.94	59.95
	3&4	75.00	61.18
1970	1&2	69.30	55.72
	3&4	70.23	56.61
1971	1&2	61.88	49.37
	3&4	61.85	49.33

Table 4.4. Calculated standard errors (s) and average deviations (a.d.) between WEPP and DRAINMOD predicted water table depths for the Toledo silty clay soil at the drainage experiment of the OARDC North Central Branch, near Sandusky, Ohio.

There are a number of possible reasons that the WEPP drain flow, runoff, and water table depth predictions may be so poor for the conditions of this study. First, the 24 hour time step used to calculate these values in WEPP is large, and water table depths can change quickly during a 24 hour period. Secondly, WEPP predicts a large amount of deep seepage at the bottom of the soil profile. Because of the assumptions and concepts modeled with most drainage models, deep seepage in large amounts is rare for soils that have a so-called impermeable layer. Next, the WEPP model predicts baseline effective conductivity based upon an empirical relationship with clay content, and at least for this study, grossly underpredicted conductivity values. In addition, WEPP appears to actually be predicting a perched water table, not a water table produced with saturated conditions from the bottom of the soil profile. WEPP produces nine soil layers and it appears that the water routing calculation times between layers may produce somewhat artificial saturated conditions in an upper layer while a lower layer may not be saturated. Therefore, the first layer may became saturated very quickly while lower layers do not become saturated with the water table at the bottom of soil profile. When the first layer becomes saturated, WEPP assumes that a water table was built starting from the bottom of the soil profile and then arriving at the soil surface. In this situation, the lower layers may still be in an unsaturated condition, or their soil water content is far from the saturation. Therefore, with the soil profile saturation assumption of WEPP, the profile is transitioning between unsaturated and saturated conditions very quickly. Lastly, it seems that the water balance predictions of WEPP throughout the soil profile may not be accurate for subsurface drained cropland. The main purpose of WEPP is to predict runoff induced erosion. If it is assumed that WEPP's runoff predictions are valid for the study conditions evaluated previously (Liu et al., 1997; Savabi, 1993; Savabi et al.; 1995; Zhang et al., 1996), then it may not be important to properly model the full soil profile water balance for most soils, especially those where subsurface drainage is not an appropriate management strategy. However, Savabi et al. (1995) stated that the root zone soil water distribution is an important part of the WEPP model hydrology because the soil water content affects subsequent rainfall/runoff events, the root zone soil water content is used in the interaction between soil water and plant growth, and the soil water content is used in the residue decomposition routines. But here again, the influence of soil water conditions of the uppermost layer is very important.

4.4 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The overall purpose of the work presented in this chapter was to gain some assessment of the hydrology component of the WEPP hillslope model (Version 97.3) for cropland with subsurface drainage. The specific objective was to evaluate the runoff, drain flow, and water table depth prediction accuracy of the WEPP hillslope model against the field measured runoff and drain flow data, and predicted water table depths from DRAINMOD (Version 4.6). Three years of measured drain flow and runoff data from the drainage experiment at the OARDC North Central Branch Station (Schwab et al., 1963; 1975; and 1985) were used in this study.

Simulations using the WEPP hillslope model were conducted for the years 1969 through 1971. WEPP daily predicted drain flow and runoff were compared to the measured outflows, and WEPP daily predicted midspace water table depths were compared to those predicted by DRAINMOD. The analyses for drain flow showed that i) drain flow simulation results with WEPP produced large average deviation values when compared to the measured data; ii) daily drain flows were overpredicted for all storm events, furthermore, large amounts of daily drain flow were predicted at times when there was little or no measured drain flow; and iii) predicted cumulative drain flows at the end of the evaluation season for each year were almost four times larger than the measured drain flows.

The analyses for runoff showed that i) WEPP produced large average deviations between daily predicted and measured runoff depths; ii) WEPP overpredicted runoff for most daily storms, and overpredicted cumulative runoff for the evaluation season for all three years. Overprediction of runoff was expected considering the very low values of WEPP predicted baseline effective conductivity.

The analyses of the WEPP predicted midspace water table depth suggest that WEPP may not be truly simulating water table depth. There is no continuous water table depth prediction in WEPP, and its algorithms allow the water table to move quickly between the soil surface and bottom of the soil profile. The calculated standard errors and average deviations between WEPP and DRAINMOD predicted midspace water table depths are very large, in the range of 0.5 to 0.75 m (1.64 to 2.46 ft).

Some of the possible reasons that the WEPP drain flow, runoff, and water table depth predictions may be so poor are: the 24 hour time step used to calculate these values in WEPP is large; a large amount of deep seepage from the bottom of the soil profile was simulated by WEPP; WEPP predicted baseline conductivity values appear to be very low especially for use in drain flow calculations for poorly drained cropland; WEPP actually is predicting a perched water table, not a water table produced with saturated conditions from bottom of the soil profile; and lastly it seems that the soil water content predictions of WEPP throughout the soil profile may not be accurate for subsurface drained cropland.

For better drain flow, runoff, water table depth, and soil water content predictions with WEPP, the following suggestions are recommended. The time step should be decreased to some value less than a day such as an hour. By offering extra input values such as an option whether to simulate deep seepage or not or assign a vertical K_{sat} value with the thickness for impermeable layer, deep seepage can be controlled. As an alternative to the water balance equation used in WEPP, water balance equations used in some more sophisticated models such as DRAINMOD and SWATRE (Belmans et al., 1983) could be used. Input parameters related to prediction of water table depth based on lab or field measurements such as soil water retention and drained volume capacity should be used in WEPP. The user should be allowed the option to enter saturated hydraulic conductivity data, and use these data in place of the WEPP baseline effective conductivity for the prediction of drain flow. Lastly, the soil water distribution in the soil profile should be related to the true water table depth.

Most of the above recommendations were applied in the WEPP modification work presented in the next chapter.

4.5 REFERENCES

Alberts, E.E., M.A. Nearing, M.A. Weltz, L.M. Risse, F.B. Pierson, X.C. Zhang, J.M. Laflen and J.R. Simanton. 1995. Chapter 7. Soil component. 7.1-7.47. In WEPP technical documentation. Eds. Flanagan, D.C. and M.A. Nearing. NSERL Report No. 10. West Lafayette, Indiana. 248 p.

Ascough II, J.C., C. Baffaut, M.A. Nearing and B.Y. Liu. 1997. The WEPP watershed model: I. Hydrology and Erosion. Transactions of the ASAE 40(4):921-933.

Baffaut, C., M.A. Nearing, J.C. Ascough II and B.Y. Liu. 1997. The WEPP watershed model: II. Sensitivity analysis and discretization on small watershed. Transactions of the ASAE 40(4):935-943.

Baumer, Otto W. 1989. Predicting unsaturated hydraulic parameters. p.341:354. In M. Th. van Genuchten and F.J. Leij, and L.J. Lund (Eds.) Proceedings of the international workshop on indirect methods for estimating the hydraulic properties of unsaturated soils. Riverside, California, October 11-13. U.S. Dept. of Agriculture: Dept. of Soil and Environmental Sciences, University of California, c1992. 718 p.

Belmans, C., J.G. Wesseling and R.A. Feddes. 1983. Simulation model of the water balance of a cropped soil: SWATRE. J. Hydrology 63(1983):271-286.

Chung, S.O., A.D. Ward and C.W. Schalk. 1992. Evaluation of the hydrologic component of the ADAPT water table management model. Transactions of the ASAE 35(2):571-579.

Deer-Ascough, L.A., G.A. Weesies, J.C. Ascough II, J.M. Laflen. 1995. Plant Parameter Database for Erosion Prediction Models. 1995. Applied Engineering in Agriculture. ASAE 11(5):659-666

Fausey, N.R. 1999. Personal communication. Research leader, USDA-ARS Soil Drainage Research Unit, Columbus, Ohio.

Flanagan, D.C. and M.A. Nearing (Eds.). 1995. WEPP technical documentation. NSERL Report No. 10. West Lafayette, Indiana. 284 p.

Flanagan, D.C. and S.J. Livingston (Eds.). 1995. WEPP user summary. NSERL Report No. 11. West Lafayette, Indiana. 131 p.

Hooghoudt, S.B. 1940. Algemeene beschouwing van het probleem van de detailontwatering en de infiltratie door middel van parallel loopende drains, greppels, slooteen, en kanalen. Versl. Landbouwk. Onderz. 46(14)B. Algemeene Landsdrukkerij, 's-Gravenhage, 193 p.

Jensen, M.E. (Ed.). 1974. Consumptive use of water and irrigation requirements. Rep. Tech. Com. on Irrig. Water Requirements, Irrig. and Drain. Div. ASCE. 227 pp.

Kirkham, D. 1957. II. Theory of land drainage, III. The ponded water case. p:139-181. In J. N. Luthin (Ed.). Drainage of Agricultural Lands. Agronomy Monograph No. 7, American Society of Agronomy, Madison, Wisconsin. 620 p.

Lane, L.J. and M.A. Nearing (Eds.). 1989. USDA-Water erosion prediction project: Hillslope profile model documentation. NSERL Rep. No. 2, USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, Indiana. 265 p.

Liu, B.Y., M.A. Nearing, C. Baffaut and J.C. Ascough II. 1997. The WEPP watershed model: III. Comparisons to measured data from small watersheds. Transactions of the ASAE 40(4):945-952.

Nearing, M.A., D.I. Page, J.R. Simanton, and L.J. Lane. 1989. Determining erodibility parameters from rangeland field data for a process-based erosion model. Transactions of the ASAE 32(3):919-924.

Penman, H.L. 1963. Vegetation and Hydrology. Tech. Com. No. 53, Commonwealth Bureau of Sols, Harpenden, England. 125 p.

Savabi, M.R., 1993. Modeling subsurface drainage and surface runoff with WEPP. J. of Irrigation and Drainage Engineering, ASCE 119(4):801-813.

Savabi, M.R., R.W. Skaggs and C.A. Onstad. 1995. Chapter 6. Subsurface hydrology. 6.1-6.14. In WEPP technical documentation. Eds. Flanagan, D.C. and M.A. Nearing. NSERL Report No. 10. West Lafayette, Indiana. 248 p.

Savabi, M.R. and J.R. Williams. 1995. Chapter 5. Water balance and percolation. 5.1-5.14. In WEPP technical documentation. Eds. Flanagan, D.C. and M.A. Nearing. NSERL Report No. 10. West Lafayette, Indiana. 248 p.

Schwab, G.O., T.J. Thiel, G.S. Taylor and J.L. Fouss. 1963.Tile and surface drainage of clay soils. Research Bulletin 935, Departments of Agricultural Engineering and Agronomy, Ohio Agricultural Experiment Station Wooster, Ohio. 47 p.

Schwab, G.O., N.R. Fausey and C.R. Weaver. 1975. Tile and surface drainage of clay soils. Research Bulletin 1081. Ohio Agricultural Research and Development Center, Wooster, Ohio. 37 p.

Schwab, G.O., N.R. Fausey, E.D. Desmond and J.R. Holman. 1985. Tile and surface drainage of clay soils. Research Bulletin 1166, Ohio Agricultural Research and Development Center, Wooster, Ohio. 29 p.

Skaggs, R.W. 1978. A water management model for shallow water table soils. Report No. 134. Raleigh, North Carolina. Water Resources Research Institute, Univ. of North Carolina. 175 p.

Skaggs, R.W. 1980. DRAINMOD Reference Report. Methods for design and evaluation of drainage-water management systems for soils with high water tables. North Carolina State University, Raleigh, North Carolina. 177 p.

Skaggs, R.W. 1982. Field evaluation of a water management simulation model. Transactions of the ASAE 25(3):666-674.

Skaggs, R.W., N.R. Fausey and B.H. Nolte. 1981. Water management model evaluation for North Central Ohio. Transactions of the ASAE 24(4):922-928.

Van Schilfgaarde, J. 1963. Design of tile drainage for falling water tables. J. Irrigation and Drainage Engineering ASCE 89(IR2):1-11.

Williams, J.R., A.D. Nicks and J.G. Arnold. 1985. Simulator for water resources in rural basins. J. Hydraulic Engineering ASCE 3(6):970-986.

Zhang, X.C., M.A. Nearing, L.M. Risse and K.C. McGregor. 1996. Evaluation of WEPP runoff and soil loss predictions using natural runoff plot data. Transactions of the ASAE39(3):855-863.

CHAPTER 5

MODIFICATION OF THE WEPP HILLSLOPE MODEL TO INCORPORATE WATER TABLE MANAGEMENT PRACTICES

5.1 INTRODUCTION

Water table management is the management, control, and/or regulation of soil-water conditions in the profile of agricultural soils. Water table management practices include subsurface drainage, controlled drainage, and subirrigation. Subsurface drainage is used to lower the water table and to create an aerated region within the plant root zone. Subsurface drainage improves trafficability, enhances field conditions for planting and harvesting, and helps decrease crop damage resulting from saturated soil and standing water (Brown et al., 1997). At the same time excessive drainage may help reduce the availability of soil water for plants, and it enhances the export of nitrate-nitrogen from the plant root zone. Under these conditions, controlled drainage and subirrigation can be used to help conserve some soil water, maintain an optimum soil water condition for supplying water to plants, supplying irrigation water for crop growth as well as reducing excess water damage, and decreasing the potential for nitrate-nitrogen export.

Controlled drainage can be defined as any drainage system that allows drainage only after the water level in the drainage ditch, pump sump or water table in the field has risen to a preset weir level. This kind of water table management practice helps keep water available for plant use longer than does subsurface drainage. It is also used to recharge the water table between growing seasons.

Subirrigation is similar to controlled drainage. The main difference is that water is pumped into the drainage outlet to maintain the outlet water level at a set point, or weir elevation. In a subirrigation system, one system is used to provide both drainage and irrigation water for crop production. Irrigation water is supplied through the subsurface drainage system using control structures to regulate the water table levels.

Drainage usually increases total outflow from fields. Some studies (Bengston et al., 1984; Istok and Kling, 1983; Skaggs et al., 1982) indicated that improvement in subsurface drainage decreased runoff and soil loss. Therefore, drainage can be used to control erosion.

Analyses of the relationships between precipitation and runoff, water table depth and runoff, water table depth and drain flow, water table depth and upflux, nutrient and pesticide losses, and sediment yield and runoff are important in understanding and simulating the effects of these water table management practices. In addition to runoff, drain flow, and upflux determination, water table depth is also important for determining soil water distribution in the root zone. Soil water content affects rainfall/runoff events, plant growth, and residue decomposition. For these kinds of analyses, a number of approximate models have been developed. The Water Erosion Prediction Project (WEPP) model (Ascough II et al., 1997; Baffaut et al., 1997; Flanagan and Livingston, 1995; Flanagan and Nearing, 1995; Lane and Nearing, 1989; Nearing et al, 1989; and Liu et al., 1997) has the potential to model hydrologic and erosional processes.

WEPP is a physically-based erosion model that may be considered a new generation erosion prediction technology. WEPP is being used to estimate sediment yield and runoff by interrill and rill erosion, and erosion by concentrated flow in field-sized areas. Furthermore, this model predicts sediment deposition from concentrated flow into channels and impoundments. Some advantages of the WEPP model over similar erosion prediction models are:

i) In WEPP, the surface and subsurface hydrology are linked with the soil erosion processes. Water table management models like ADAPT (Chung, 1988), GLEAMS (Leonard et al., 1987), EPIC-WT (Sabbagh et al., 1993), and GLEAMS-SWAT (Reyes et al., 1994) also have hydrology components that are linked to soil erosion processes. However, the erosion routines in these models are not as state of the art as in WEPP.

ii) Several drainage simulation models such as DRAINMOD (Skaggs, 1978), SWATRE (Belmans et al., 1983), and PREFLO (Workman and Skaggs, 1990) are water balance models, but lack linkage between hydrology and soil erosion processes.

iii) In comparison to the models mentioned above, WEPP includes impoundment and channel components that can be used to route runoff and sediment through a watershed.

iv) The hillslope or landscape profile application of the model provides a) state of the art capability for estimating spatial and temporal distributions of net soil loss (or gain in the case of deposition) for an entire hillslope or for discrete points on the hillslope; b) the ability to extrapolate over a broad range of conditions that may not be practical or economical to field test (Nearing et al., 1989); and c) the ability to simulate non-uniform soils and management along a hillslope.

v) WEPP reflects the effects of land use changes due to agricultural, range, and forestry practices. It models spatial and temporal variability of the factors affecting the surface and subsurface water quality and quantity along a single hillslope or over a small watershed (Savabi et al., 1995a).

Most of the advantages of the WEPP model as listed above are related to the erosion prediction components of the model. After evaluating the hydrology component of the WEPP hillslope model in Chapter 4, it can be said that model has the following limitations:

i) The water table depth prediction capability of the model is poor compared to the capabilities of DRAINMOD. In addition, WEPP's water table depth simulations are not continuous.

ii) Runoff, infiltration, soil water content distribution, and upflux by plant roots are not calculated in relation to water table depth.

iii) The time step to calculate drain flow and water table depth is 24 hours, which is probably too large for accurate predictions, especially when the water table close to the soil surface.

iv) To predict subsurface drainage flow, the model uses only the Hooghoudt equation (Hooghoudt, 1940). DRAINMOD uses the Kirkham (Kirkham, 1957) and Hooghoudt equations.

v) WEPP's predicted water table depth and drain flow are not provided to the user in an output file.

vi) Except for the work discussed early in Chapter 4, no research has appropriately evaluated the current water table depth and drain flow prediction capabilities of WEPP.

vii) The current version of WEPP can not be used to simulate runoff, water table depth, sediment yield, and drainage flow from a field on which a controlled drainage or subirrigation system is planned or present.

viii) The model may overestimate water loss by deep seepage, especially for poorly drained soils in humid regions.

ix) The model does not contain any option for the user to use field or lab measured saturated hydraulic conductivity values which might be used to predict drain flows by the model.

The Water Erosion Prediction Project-Water Table Management (WEPP-WTM) model was developed to address some of the above limitations of WEPP. This development work mainly focused on the procedures used to predict runoff, drain flow, and water table depth with an hourly time step. Attributes of the predicted runoff event such as runoff depth, peak, and duration were linked with the WEPP erosion prediction algorithms to calculate the erosion parameters from hillslopes on which water table management systems are planned or present. The purpose of this chapter is to present the procedures used to develop WEPP-WTM.

5.2 MODEL MODIFICATIONS

Version 97.3 of the WEPP model was modified to develop WEPP-WTM. For this modification, Digital Visual Fortran (Version 5.0) was used as the fortran compiler. The main modifications were made in two subroutine files of the WEPP source code. In the first file (input.for), the new (WEPP-WTM) and old model (original WEPP) input data are read and, if needed, additional calculations are made to prepare the parameters that are then used in the simulation algorithms of WEPP-WTM. These calculations include upflux, soil water content, unsaturated hydraulic conductivity, and drained volume if water table depth relationships for these parameters are entered to as input. The flowchart showing these calculations is presented in Figure 5.1. The letter A connects Figure 5.1 to 5.2.

The second file is the water balance file (watbal.for), where all calculations for the water balance simulation of WEPP-WTM were modified to accommodate an hourly time step. Other subroutines needed for the water balance simulation were called from this file. The flowchart is given in Figure 5.2. The letter C in this figure represents the connection to the rest of the WEPP simulations. Since an hourly time step was incorporated into the water balance simulations, WEPP-WTM was developed to use the WEPP weather input file in breakpoint form. In this form, rainfall has to be entered hourly. This hourly time step should allow WEPP-WTM to better predict hourly runoff, drain flow, and water table depth. In WEPP-WTM, melted snow water (predicted by the original WEPP) and rainfall are used in place of precipitation data in the water balance routines. Saturated hydraulic conductivity values are adjusted for frozen soil conditions. These last two modifications should allow WEPP-WTM to be more applicable for the winter months of cold humid regions.

The six sections below describe the methodologies developed for WEPP-WTM for runoff, subsurface drainage, water table depth, upward flux, root depth, and evapotranspiration. Most of these procedures were modified from DRAINMOD and WEPP.

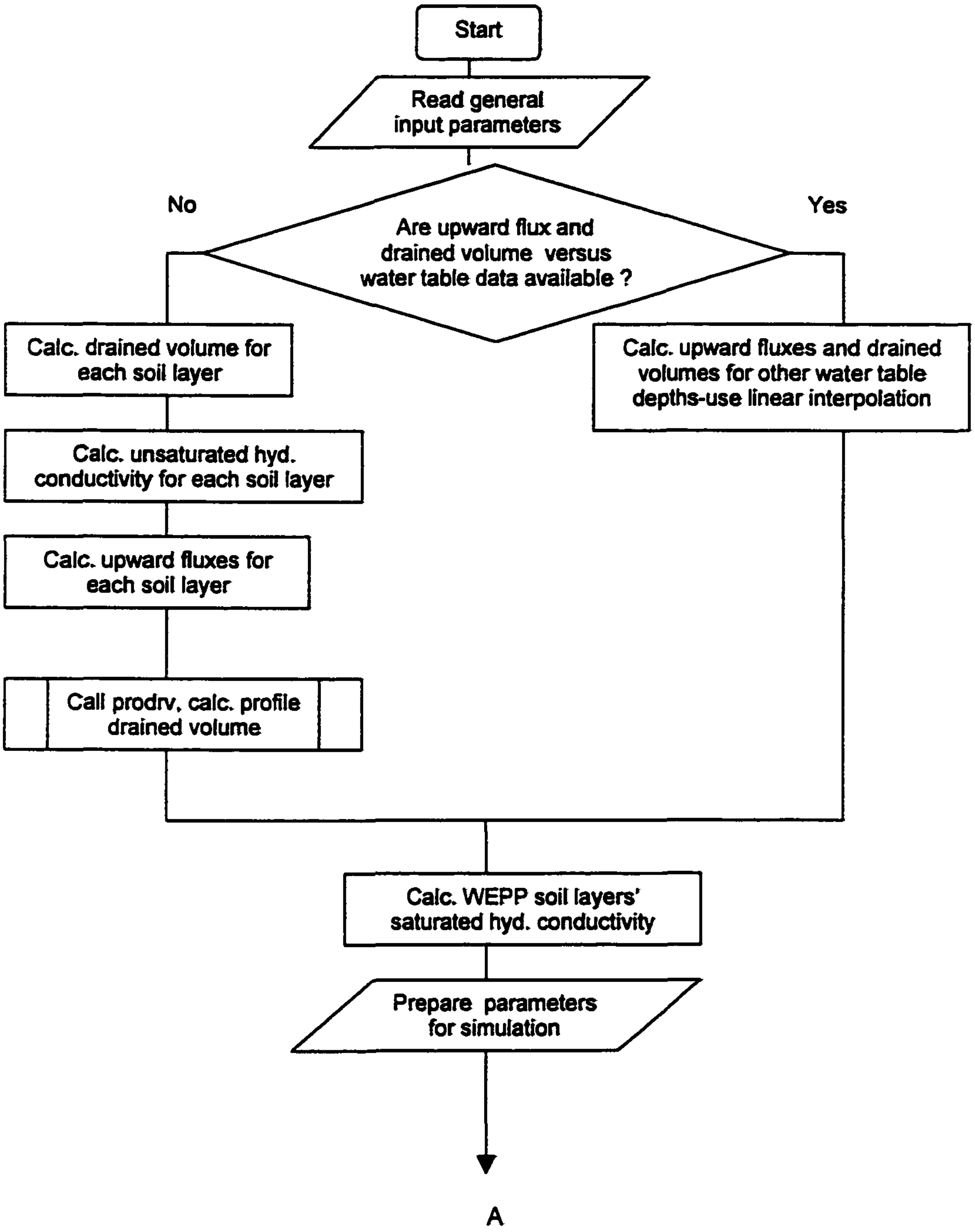

Figure 5.1. Flowchart showing the water table depth corresponding upward flux and drained volume calculations with these data related unsaturated hydraulic conductivity values with WEPP's soil layers saturated hydraulic conductivity values. All these parameters are used in the water balance simulations of WEPP-WTM.

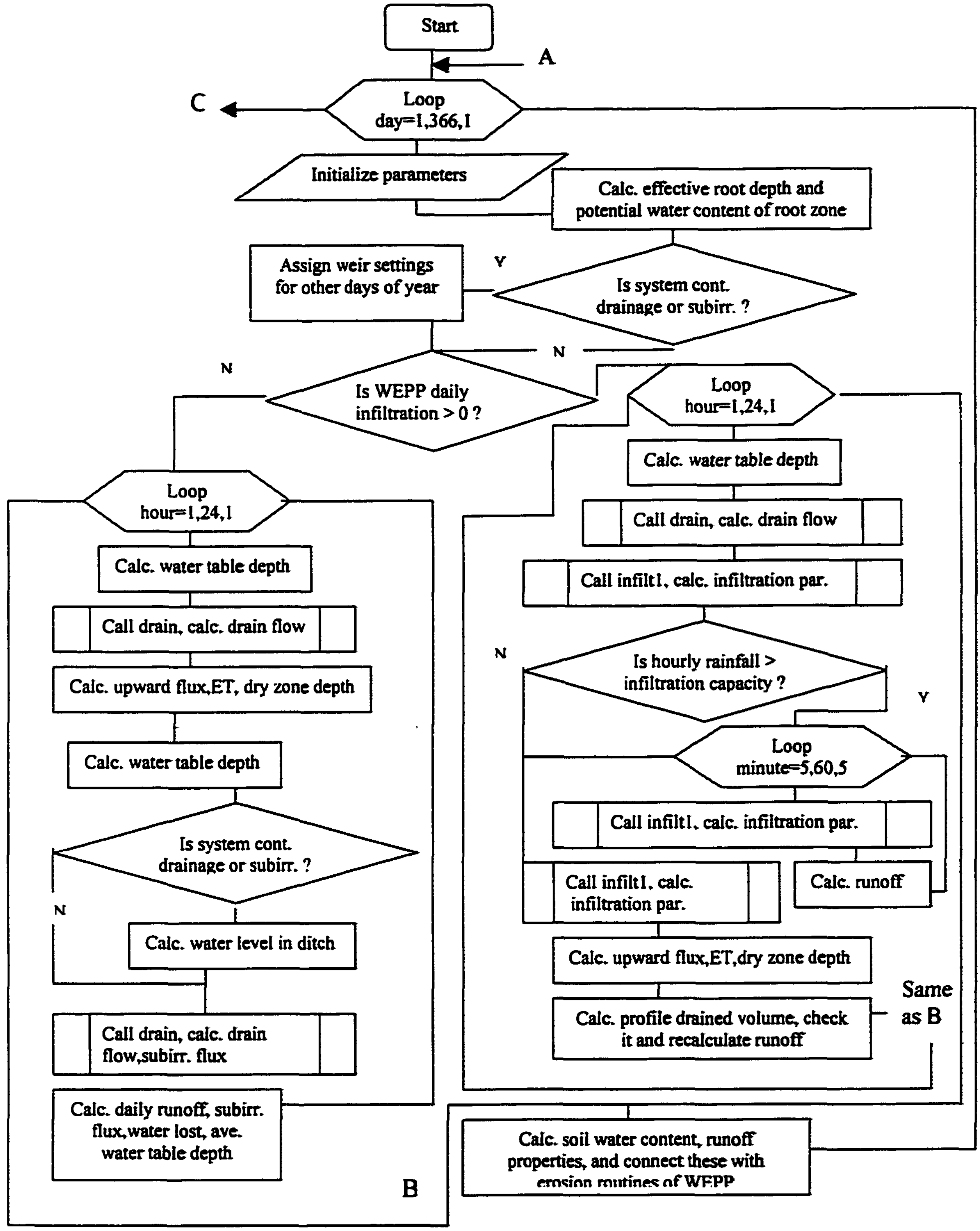

Figure 5.2. Flowchart showing the water balance calculations of WEPP-WTM.

5.2.1Runoff Modifications

Runoff in WEPP-WTM is calculated by subtracting the infiltration capacity of the soil from the rainfall rate. When hourly rainfall is greater than the infiltration capacity of the soil, a 5-minute time step is used in the infiltration routine of the model to calculate runoff. For this condition, the infiltration capacity (cm/hr) of the soil is calculated using the following Green and Ampt (1911) infiltration equation:

$$f = B + A / F \quad \text{.......... 5.1}$$

where: A and B are constants and F is the cumulative infiltration (cm). The form of this equation used in DRAINMOD (Skaggs, 1980) is the following:

$$f = K_s + K_s M S_{av} / F \quad \text{.......... 5.2}$$

where: K_s is the core method based vertical saturated hydraulic conductivity (cm/hr) of the surface layer; and M is the initial soil water deficit (%). The parameter S_{av} in Equation 5.2 is the effective suction at the wetting front (cm), which is calculated in DRAINMOD as:

$$S_{av} = \int_0^h K_r dh \quad \text{.......... 5.3}$$

where: h is the water table depth (cm); K_r is the relative hydraulic conductivity ($K(h)/K_s$); and K(h) is unsaturated hydraulic conductivity (cm/hr). When the water table is on the surface, the infiltration capacity of the soil is assumed to be equal to the drain flow plus evapotranspiration.

At the soil surface, runoff depth in WEPP-WTM is calculated using the following equation (Skaggs, 1978):

$$RO = P - (\Delta S + F) \quad \text{.......... 5.4}$$

where: RO is runoff depth (cm); P is the rainfall and/or melted snow (cm); ΔS is the change in the depth of water in the depressional storage at the soil surface; and F is the cumulative infiltration (cm). The predicted runoff is checked with the DRAINMOD water balance equation for soil profile as given below:

$$\Delta V_a = D + ET + DS - F \qquad 5.5$$

where: ΔV_a is the change in the drained volume of the soil profile (cm); D is the drain flow (or subirrigation flow) (cm); ET is the evapotranspiration (cm); F is the cumulative infiltration (cm); and DS is the deep seepage (cm). If the value of ΔV_a in Equation 5.5 becomes negative, the absolute value of ΔV_a is then assumed to be runoff. The final runoff predicted in WEPP-WTM is the absolute value of ΔV_a, if it is larger than the runoff calculated by using Equation 5.4. Otherwise, the final predicted runoff is equal to the runoff value calculated by Equation 5.4. The components considered in the water balance are shown in Figure 5.3.

The calculated runoff depth was corrected for depressional storage on the soil surface. There is an option for the user to either enter measured constant depressional storage depth value or let WEPP-WTM use the original WEPP predicted values. In the original WEPP model, the depressional storage depth is simulated as (Savabi et al, 1995b):

$$\Delta S = 0.112R_r + 0.031R_r^2 - 0.012R_r S_p \qquad 5.6$$

where: ΔS is the depressional storage (cm); R_r is the random roughness (cm); and S_p is the average slope steepness (%). This value in the WEPP model is also used to represent surface drainage. In WEPP-WTM, the sum of the predicted hourly runoff values gives the daily runoff and this value is presented in the WEPP-WTM water balance output file.

5.2.2 Subsurface Drainage, Controlled Drainage, and Subirrigation Modifications

To predict the drain flow removed from the soil profile by drain tubes or ditches, the WEPP model uses only the Hooghoudt equation (Savabi et al., 1995b) as given below:

$$Q = \frac{8K_e d_e H + 4K_e H^2}{L^2} \qquad 5.7$$

where: Q is the drain flow depth (cm/hr); H is the midspace water table elevation above drain (cm); K_e is the equivalent saturated hydraulic conductivity (cm/hr); L is the drain spacing (cm); and d_e is the equivalent depth (cm). In WEPP, the parameter d_e for the condition $0 < d/L < 0.3$ is calculated as:

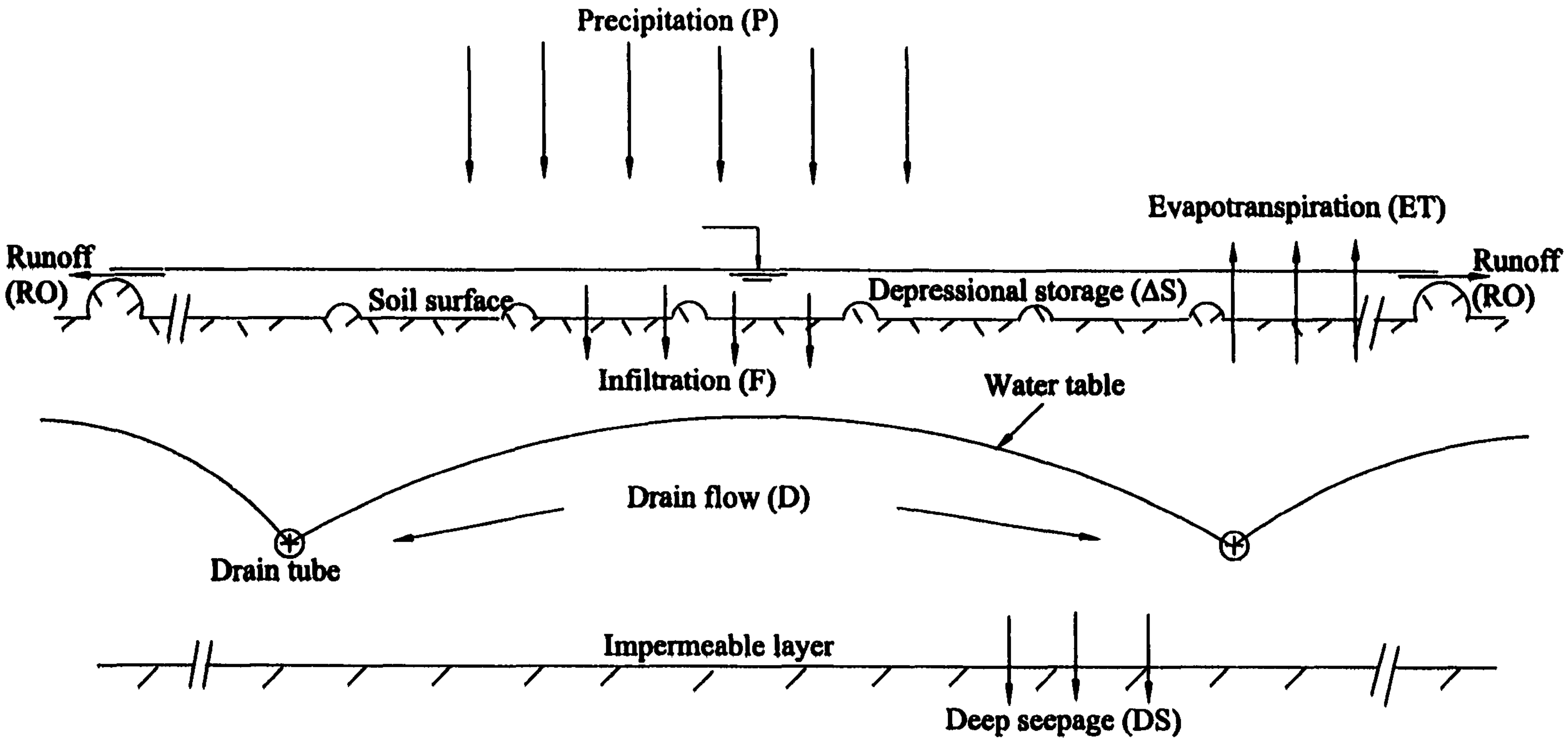

Figure 5.3 The components considered in the water balance of WEPP-WTM model.

$$d_e = \frac{d}{1 + \frac{d}{L}(\frac{8}{\pi}\ln(\frac{d}{r_e}) - 3.4)} \qquad 5.8$$

For the condition d/L ≥ 0.3, a value for d_e is calculated as:

$$d_e = \frac{L\pi}{8(\ln(\frac{L}{r_e}) - 1.15)} \qquad 5.9$$

where: d is the depth from the center of the drain to the impermeable layer (cm); and r_e is the effective radius of drain tubes (cm). In Equation 5.8, the constant 3.4 is an approximate value for the parameter α (a function of d/L). In WEPP-WTM, the constant 3.4 shown in Equation 5.8 is replaced with the parameter α, calculated as (Moody and Asce, 1966):

$$\alpha = 3.55 - \frac{1.6d}{L} + 2(\frac{2}{L})^2 \qquad 5.9$$

In WEPP-WTM, the Hooghoudt equation is used when water table is at least 0.5 cm (0.2 in) below the soil surface (drawdown condition). When the water table is at the soil surface (ponded condition), the Kirkham equation is used, as given below:

$$Q = 4\pi K_e(t + b - r)/gL \qquad 5.11$$

where:

$$g = 2\ln(\frac{\tan(\pi(2d - r)/4h)}{\tan(\pi r/4h)}) \qquad 5.12$$

h is the depth of soil profile (cm); r is the radius of the drain tube (cm); t is the depth of water on the surface (cm); and b is the depth from the surface to the drains (cm). The equivalent saturated hydraulic conductivity (K_e) in both the Kirkham and Hooghoudt equations is calculated for the saturated section of the soil profile using the following equation (Skaggs, 1980):

$$K_e = \frac{K_{sat1}d_1 + K_{sat2}D_2 + K_{sat3}D_3 + K_{sat4}D_4}{d_1 + D_2 + D_3 + D_4} \quad \text{.......} 5.13$$

where: K_e is the equivalent saturated hydraulic conductivity (cm/hr) when midspace water table elevation from the impermeable layer was $d_1+D_2+D_3+D_4$; K_{sat1}, K_{sat2}, K_{sat3} and K_{sat4} are saturated hydraulic conductivity values (cm/hr) of the first, second, third, and fourth soil layers, respectively; d_1 is the midspace water table elevation from the bottom of the first soil layer (cm); D_2, D_3 and D_4 are the second, third and fourth soil layer thicknesses (cm), respectively.

In the soil input file of WEPP-WTM, the saturated hydraulic conductivity value for each soil layer is entered as input data. The description of the soil input file is given in Table L.1 (Appendix L). Depending upon the user's choice (ksflag in soil input file), the saturated hydraulic conductivity values can be adjusted within the continuous simulation as a function of soil management and plant characteristics, or they can remain constants. Furthermore, for winter months simulations, the saturated hydraulic conductivity values can be adjusted for frozen soil conditions. For this adjustment, the following original WEPP equations (Alberts et al., 1995) were used:

$$FS_a = 3.75e^{-0.26F_Q} \quad \text{.......} 5.14$$

$$F_Q = \frac{Q_f}{Q_{fc}}100 \quad \text{.......} 5.15$$

$$K_{frozen} = K_{unfrozen}(FS_a) \quad \text{.......} 5.16$$

where: FS_a is the hydraulic conductivity adjustment factor for frozen soil conditions; Q_f is the volumetric soil water content at the freezing point (m^3/m^3); Q_{fc} is the volumetric soil water content at field capacity; K_{frozen} is the saturated hydraulic conductivity of the frozen soil layer (mm/hr), and $K_{unfrozen}$ is the saturated hydraulic conductivity (K_{sat}) of the soil layer (mm/hr).

When controlled drainage or subirrigation is used, the water table level is controlled by a weir. The weir is set at a given elevation at the drainage outlet. In WEPP-WTM, weir settings (elevations), along with their respective dates and subirrigation or controlled drainage flag code, are entered as input in the drainage section of the plant/management input file. The description of the drainage section of the plant/management input file is given in Table L.2 (Appendix L). For subirrigation, the water level in the drainage outlet is held at the specified weir setting elevation by pumping water into the subirrigation system (at a head stand). For controlled drainage, the weir is set at a given elevation, and the outlet ditch or stream water level may be at or below the weir elevation depending on runoff and drainage flow coming to the ditch or stream from the system (Skaggs, 1978).

After considering the chosen water table management option, WEPP-WTM checks for the weir setting for the day. If the weir setting is lower than the drain depth of the water table management system, the system is simulated as being in a free drainage mode (conventional subsurface drainage) without regard to the chosen option. In some subirrigation and controlled drainage systems, drainage flow and runoff from these systems may not go to the same outlet ditch or stream. In WEPP-WTM, the user can choose this option.

Ditch side slopes and bottom depths are entered in the drainage section of the plant/management input file (Appendix L, Table L.2). If the side slope is entered as zero, the model assumes that the shape of the ditch is rectangular, otherwise it is trapezoidal. The amount of water lost from the system and that remaining in the ditch or stream is calculated. The total volume of water stored and water level in a trapezoidal ditch are calculated using the following equations as described by Skaggs (1978), respectively:

$$CV = bYD + sYD^2 \qquad 5.17$$

$$YD = \frac{-b}{2s} + \left\{ \left(\frac{b}{s}\right)^2 + \frac{4CV}{s} \right\}^{1/2} / 2 \qquad 5.18$$

where: CV is the total volume of water stored in the ditch (cm^3 per unit length of ditch); s is the ditch side slope (ratio of run over rise); b is the bottom width of the ditch (cm); and YD is the water level in the ditch (cm). Similar equations were developed for the rectangular shaped ditches. For these modifications, an equation was developed to calculate the change in CV as:

$$\Delta CV = (R + q)L \qquad 5.19$$

where: R is the runoff (cm/hr); q is the drain flow (cm/hr); and L is the drain spacing (cm).

When subirrigation is used, the water level in the ditch is raised by pumping water into the ditch. The following equation is used to predict subirrigation flux (Skaggs, 1980):

$$Q = \frac{4K_e m(2h_o + \frac{h_o}{D_o} m)}{L^2} \quad \text{.......} 5.20$$

where: D_0 is the pressure head at a point on the impermeable layer just below the drain calculated as $y_0 + d$; h_0 is the equivalent pressure head at a point on the impermeable layer just below the drain calculated as $y_0 + d_e$; y_0 is water table elevation above the drain (cm); and m is midspace water table elevation minus the water table elevation at the drain (cm). In WEPP-WTM, the sum of the hourly predicted drain flows for a day gives the daily drainage flow for that day. The sign of the subirrigation flow and drain flow returning from a ditch to the controlled drainage system is a negative value. Daily drainage flows and water losses from the systems are given in the WEPP-WTM water balance output file.

5.2.3 Water Table Modifications

Drain flow and ET calculations in WEPP-WTM depend on the predicted midspace water table depths. In the water balance routines, the water table depth is calculated at the end of every hour. The water table depth based on the soil water content distribution in the soil profile is calculated hourly. The soil water content below the water table is assumed to be saturated. Above the water table, the soil water is assumed to be equilibrium with the water table depth. For deep water table depths, a dry zone starting from the soil surface can develop, but this depends on the ET rate, root depth, and the unsaturated hydraulic conductivity of the soil. The drained volume-water table depth relationship is used to simulate fluctuations of the water table, and therefore allows WEPP-WTM to determine how far the water table falls or rises when a given amount of water is removed or added. The following equation was used to develop this relationship (Skaggs, 1980):

$$V_d = \int_0^{y_1} (Q_0(y) - Q(y))dy \qquad 5.21$$

where: V_d is the volume drained (cm^3/cm^3); y_l is the water table depth (cm); $Q_0(y)$ is the saturated soil water content (cm^3/cm^3); $Q(y)$ is the soil water content for a water table depth of y (cm^3/cm^3); and y is any water table depth between zero and y_l (cm). In the model, the parameter V_d is calculated for a maximum of 10 soil layers. The parameters Q_0 and Q for each soil layer are calculated from the soil water content versus pressure data that may be entered into the soil input file of WEPP-WTM. As an alternative to this calculation, the user may substitute another drained volume-water table depth relationship (Appendix L, Table L.1).

5.2.4 Upward Flux Modifications

The upflux or capillary rise from a water table is important to transmit the water from water table to the plant roots, therefore upflux is an important phenomenon in each of the three components of water table management systems. In particular, subirrigation systems allow water to be introduced to the subsurface drains via water table control structures. As the water table is raised, water can be transmitted by capillary rise to the root zone to satisfy the ET demand by the crops. Upward flux affects the water table draw down since soil profile water is lost by upward flux. The upward flux rate also affects the ET. For these reasons, it is desirable to determine the steady upward flux from a water table over the range of possible water table depths. For a particular soil, this relationship can be developed and then provided as input to the model.

WEPP-WTM has two options for obtaining the upflux versus water table depth relationship. The user can input a known relationship into the soil input file (Appendix L, Table L.1). If the user does not have this relationship, WEPP-WTM can develop this relationship using a method developed by Memon et al. (1986). They used the concept of matrix flux potential (MFLP) as discussed by Shaykewich and Stroosnijder (1977), and defined the MFLP function as follows:

$$MFLP(h) = \int_{ho}^{h\max} K(h)dh \qquad 5.22$$

where: MFLP(h) is the matrix flux potential (cm^2/hr) at the water table depth h; hmax is the maximum allowable pressure head (cm) at the center of the effective root zone; and ho is the pressure head at the water table (cm). Memon et al. noted that Taylor and Ashcroft (1972) presented values of hmax for various crops. For example, a hmax value of 12000 is used for corn. The procedure to use the matrix flux potential approach is as follows. A matrix of MFLP values and unsaturated hydraulic conductivity values are determined for the anticipated range of water table depths. Then, for each of a range of assumed constant upflux (q) values, the water table depth (z) which corresponds to each constant value of q is calculated as follows (Memon et al., 1986):

$$Z = \sum_{i=1}^{i=h\max} \frac{MFLP_{i+1} - MFLP_i}{q + \left[K(h_{i+1}) + K(h_i)\right]/2} \qquad \text{.......} 5.23$$

where: Z is the water table depth (cm) corresponding to the assumed constant upflux, q (cm/hr); MFLP was defined above; K(h) is unsaturated hydraulic conductivity of surface soil when water table depth is h (cm); and i = 1 to hmax (cm) with increments of 1. An adjustment was made to get an upward flux value equal to the vertical saturated hydraulic conductivity of the first soil layer when the water table is on the soil surface. Upward flux values for other water table depths that are between those calculated with equation 5.23 can be determined using linear interpolation.

The unsaturated hydraulic conductivity (K(h)) for each soil layer was calculated using the Millington and Quirk equation (Millington and Quirk, 1959) as given below:

$$K(Q_i) = 230 K_{sat} \left(\frac{Q_i}{Q_s}\right)^{4/3} \frac{\sum_{j=1}^{m} (2j+1-2i)/h_j^2}{\sum_{j=1}^{m} (2j-1)/h_j^2} \qquad \text{.......} 5.24$$

where: K(Q$_i$) is the unsaturated hydraulic conductivity (cm/hr) at water content Q$_i$ (cm^3/cm^3); K$_{sat}$ is the core method based saturated vertical hydraulic conductivity (cm/hr); Q$_s$ is the water content at saturation (cm^3/cm^3); m is the number of water content increments; h$_j$ is the pressure (cm of water) which corresponds to the water content; and j and i are indices. Values for K(h) are found from the K(Q) relationships using linear interpolation.

5.2.5 Root Depth Modifications

In WEPP-WTM, the effective root depth is used to calculate the zone from which water can be removed as necessary to supply the ET demand of the crops. The root depth for annual crops in WEPP is simulated using an equation by Arnold et al. (1995), which was adopted from Borg and Williams (1986) as:

$$R_d = (R_{dx})_j \left[0.5 + 0.5\sin\left[3.03(HUI) - 1.47\right]\right] \quad \text{5.25}$$

where: R_d is the root depth (m); R_{dx} is the maximum root depth (m) for crop j; HUI is the heat unit index calculated as hu_i / phu_j, where: hu_i is the heat units for day i received so far; and phu_j is the potential heat units required for maturity of crop j. In WEPP-WTM, 20 percent of the root depth is used as the effective root depth. When the predicted root depth is less than 3 cm (1.2 in) or plants do not exist in the field during a particular simulation time, a 3 cm (1.2 in) root depth is then used to reflect the soil depth from which water may be evaporated.

5.2.6 Evapotranspiration

For WEPP-WTM, the calculated reference potential ET (PET) algorithms from WEPP are used. In WEPP, there are two methods to calculate PET. The first is the Penman method (Jensen, 1974; Penman, 1963), which is applicable if daily radiation, temperature, wind, and dew point temperature or relative humidity data are available. The second is the Priestley-Taylor (1972) method, which is applicable when only daily solar radiation and temperature data are available. In addition to these two methods, WEPP-WTM allows the user to use of daily measured PET data if available (Appendix L, Table L.1). For the use of daily PET data, a file system similar to that used in DRAINMOD is used.

5.3 SUMMARY

The purpose of the work presented in this chapter was to modify WEPP hillslope model and to present the procedures and algorithms used in this modification.

The WEPP hillslope model (Version 97.3) was modified to help improve the water balance, runoff, drain flow, and water table depth prediction capabilities of WEPP for cropland where water table management systems exist or are planned. Attributes of the predicted runoff event such as runoff depth, peak, and duration were linked with the WEPP erosion prediction algorithms to calculate the erosion parameters from hillslopes on which subsurface drainage, controlled drainage, or subirrigation water table management systems are planned or present. The modified model is WEPP-Water Table Management (WTM). Most of the procedures (subirrigation, subsurface drainage, and controlled drainage flow predictions, water table depth versus drained volume and unsaturated hydraulic conductivity relationships, and infiltration) used in the modified water balance simulations were taken from DRAINMOD. WEPP hillslope model predicted PET, plant root depth, depressional storage depth, and saturated hydraulic conductivity adjustments for frozen soils were used. Upward flux rate from the water table was calculated using the concept of matrix flux potential by Memon et al. (1986). The estimated runoff related sediment yield was predicted using the erosion prediction components of WEPP hillslope model.

WEPP-WTM predicts hourly runoff, drain flow, subirrigation flow, controlled drainage and subirrigation excess flows, water table depth, and daily sediment yields from the fields on which any of the water table management practice (or combination) is planned or present. Daily outputs are presented in the water balance output file of WEPP-WTM.

WEPP-WTM offers options to the user to use field or lab measured soil water retention data, water table depth-upward flux and drained volume data, saturated hydraulic conductivity of soil layers, and daily PET values. The model also allows the user to control deep seepage and depressional storage depth.

The developed WEPP-WTM can be used especially for slightly sloped field sized areas at which subsurface lateral water lost from soil profile is negligible. In addition, this model was developed for humid regions where the water table is close to the soil surface most of the year.

The applicability and accuracy of WEPP-WTM predictions are evaluated with measured field data in the next chapter.

5.4 REFERENCES

Alberts, E.E., M.A. Nearing, M.A. Weltz, L.M. Risse, F.B. Pierson, X.C. Zhang, J.M. Laflen and J.R. Simanton. 1995. Chapter 7. Soil component. 7.1-7.47. In WEPP technical documentation. Eds. Flanagan, D.C. and M.A. Nearing. NSERL Report No. 10. West Lafayette, Indiana. 248 p.

Arnold, J.G., M.A. Weltz, E.E. Alberts and D.C. Flanagan. 1995. Chapter 8. Plant growth component. 8.1-8.41. In WEPP technical documentation. Eds. Flanagan, D.C. and M.A. Nearing. NSERL Report No. 10. West Lafayette, Indiana. 248 p.

Ascough II, J.C., C. Baffaut, M.A. Nearing and B.Y. Liu. 1997. The WEPP watershed model: I. Hydrology and erosion. Transactions of the ASAE 40(4):921-933.

Baffaut, C., M.A. Nearing, J.C. Ascough II and B.Y. Liu. 1997. The WEPP watershed model: II. Sensitivity analysis and discretization on small watershed. Transactions of the ASAE 40(4):935-943.

Belmans, C., J.G. Wesseling and R.A. Feddes. 1983. Simulation model of the water balance of a cropped soil: SWATRE. J. Hydrology 63(1983):271-286.

Bengston, R.L., C.E. Carter, H.F. Morris and J.G. Kowalczuk. 1984. Reducing water pollution with subsurface drainage. Transactions of the ASAE 27(1):80-83.

Borg, H. and D.W. Williams. 1986. Depth development of roots with time: An empirical description. Transactions of the ASAE 29(1):194-197.

Brown, L.C., A. Ward and N.R. Fausey. 1997. Agricultural water table management systems. Extension Fact Sheet AEX 321-97. The Ohio State University Extension, Columbus. 8 p.

Chung, S.O. 1988. ADAPT – A model to simulate pesticide movement into drain tiles. Master Thesis. Ohio State University, Columbus. 241 p.

Flanagan, D.C. and M.A. Nearing (Eds.). 1995. WEPP technical documentation. NSERL Report No. 10. West Lafayette, Indiana. 284 p.

Flanagan, D.C. and S.J. Livingston (Eds.). 1995. WEPP user summary. NSERL Report No. 11. West Lafayette, Indiana. 131 p.

Green, W.H. and Ampt, G.A. 1911. Studies on soil physics. I. Flow of air and water through soils. J. Agricultural Science 4(Part I):1-24.

Hooghoudt, S.B. 1940. Algemeene beschouwing van het probleem van de detailontwatering en de infiltratie door middel van parallel loopende drains, greppels, slooteen, en kanalen. Versl. Landbouwk. Onderz. 46(14)B. Algemeene Landsdrukkerij, 's-Gravenhage, 193 p.

Istok, J.D. and G.F. Kling. 1983. Effect of subsurface drainage on runoff and sediment yield from an agricultural watershed in Western Oregon, U.S.A. J. Hydrology 65(1983):279-291.

Jensen, M.E. (Ed.). 1974. Consumptive use of water and irrigation requirements. Rep. Tech. Com. on Irrig. Water Requirements, Irrig. and Drain. Div. ASCE. 227 pp.

Kirkham, D. 1957. II. Theory of land drainage, III. The ponded water case. p:139-181. In J. N. Luthin (Ed.). Drainage of Agricultural Lands. Agronomy Monograph No. 7, American Society of Agronomy, Madison, Wisconsin. 620 p.

Lane, L.J. and M.A. Nearing (Eds.). 1989. USDA-Water erosion prediction project: Hillslope profile model documentation. NSERL Rep. No. 2, USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, Indiana. 265 p.

Leonard, R.A., W.G. Knisel and D.A. Still. 1987. GLEAMS: Groundwater loading effects of agricultural management systems. Transactions of the ASAE 30(5):1403-1418.

Liu, B.Y., M.A. Nearing, C. Baffaut and J.C. Ascough II. 1997. The WEPP watershed model: III. Comparisons to measured data from small watersheds. Transactions of the ASAE 40(4):945-952.

Memon, N.A., C.A. Madramootoo, S.O. Prasher and R.S. Broughton. 1986. A method for estimating the steady upward flux from a water table. Transactions of the ASAE 29(6):1646-1649.

Millington, R.J. and J.P. Quirk. 1959. Permeability of porous media. Nature 183(4658):387-388.

Moody, W.T. and F. Asce. 1966. Nonlinear differential equation of drain spacing. J. Irrigation and Drainage Engineering, ASCE 92(IR2):1-9.

Nearing, M.A., D.I. Page, J.R. Simanton, and L.J. Lane. 1989. Determining erodibility parameters from rangeland field data for a process-based erosion model. Transactions of the ASAE 32(3):919-924.

Penman, H.L. 1963. Vegetation and Hydrology. Tech. Com. No. 53, Commonwealth Bureau of Sols, Harpenden, England. 125 p.

Priestly, C.H.B. and R.J. Taylor. 1972. On the assessment of surface heat flux and evaporation using large scale parameters. Monthly Weather Review 100(2):81-92

Reyes, M.R., R.L. Bengston and J.L. Fouss. 1994. GLEAMS-WT hydrology submodel modified to include subsurface drainage. Transactions of the ASAE 37(4):1115-1120.

Sabbagh, G.J., J.L. Fouss and R.L. Bengston. 1993. Comparison of EPIC-WT and DRAINMOD simulated performance of land drainage system. Transactions of the ASAE 36(1):73-79.

Savabi, M.R., D.C. Flanagan, B. Hebel and B.A. Engel. 1995a. Application of WEPP and GIS-GRASS to a small watershed in Indiana. J. Soil and Water Conservation 50(5): 477-483.

Savabi, M.R., R.W. Skaggs and C.A. Onstad. 1995b. Chapter 6. Subsurface hydrology. 6.1-6.14. In WEPP technical documentation. Eds. Flanagan, D.C. and M.A. Nearing. NSERL Report No. 10. West Lafayette, Indiana. 248 p.

Shaykewich, C.F. and L. Stroosnijder. 1977. The concept of matric flux potential applied to simulation of evaporation from soil. Neth. J. Agric. Sci. 25:63-82.

Skaggs, R.W. 1978. A water management model for shallow water table soils. Report No. 134. Raleigh, North Carolina. Water Resources Research Institute, Univ. of North Carolina. 175 p.

Skaggs, R.W. 1980. DRAINMOD Reference Report. Methods for design and evaluation of drainage-water management systems for soils with high water tables. North Carolina State University, Raleigh, North Carolina. 177 p.

Skaggs, R.W., A. Nassehzadeh-Tabrizi and G.R. Foster. 1982. Subsurface drainage effects on erosion. J. Soil and Water Conservation 37(3):167-171.

Taylor, S.A. and G.L. Ashcroft. 1972. Physical Edaphology. The physics of irrigated and non-irrigated soils. W.H. Freeman and Company, San Francisco, pp. 533.

Workman, S.R. and R.W. Skaggs. 1990. PREFLO: A water management model capable of simulating preferential flow. Transactions of the ASAE 33(6):1939-1948.

CHAPTER 6

FIELD TESTING OF THE WEPP WATER TABLE MANAGEMENT (WEPP-WTM) MODEL FOR SUBSURFACE DRAINED CROPLAND

6.1 INTRODUCTION

Water table management systems are important for agricultural productivity and for environmental quality. The use of these systems by farmers can help control excess and deficit soil-water conditions to provide better plant growth conditions for the production of food (Brown et al., 1997). The three primary components of water table management systems are: subsurface drainage, controlled drainage and subirrigation. Subsurface drainage systems help reduce runoff, and subsequently help decrease erosion and phosphorus losses to receiving waters. However, nitrate-nitrogen delivery to receiving waters may be increased. When controlled drainage and subirrigation practices are used, a reduction in offsite delivery of nitrate-nitrogen without increased phosphorus delivery is possible (Fausey et al., 1995).

Water table management models are needed to design and evaluate these systems within a watershed perspective. The Water Erosion Prediction Project (WEPP) hillslope model (Ascough II et al., 1997; Baffaut et al., 1997; Flanagan and Livingston, 1995; Flanagan and Nearing, 1995; Lane and Nearing, 1989; Liu et al., 1997; and Nearing et al., 1989) (Version 97.3) was modified to improve WEPPs ability to predict runoff, drain flow, and water table depths on subsurface drained cropland. The modified WEPP model, WEPP-Water Table Management (WEPP-WTM), has the ability to model runoff, drain flow, subirrigation flow, controlled drainage and subirrigation excess flows, water table depth, soil water content distribution in soil profile, and sediment yield from cropland on which any combination of the three water table management system components is present or planned. The modification algorithms and procedures were described in Chapter 5.

The objective of this chapter is to test and evaluate the performance of the WEPP-WTM model in simulating of runoff, drain flow, and water table depth for subsurface cropland conditions. WEPP-WTM predictions will be evaluated against measured data.

6.2 MATERIALS AND METHODS

6.2.1 Experimental Sites

In this study, data from two subsurface drained cropland field sites were used to test and evaluate the runoff, drain flow and water table depth prediction accuracy of WEPP-WTM. Field data obtained from the combination plots (surface and subsurface drained) of the drainage experiment of Schwab et al. (1963; 1975; and 1985) at the Ohio Agricultural Research and Development Center (OARDC) North Central Branch, near Sandusky, Ohio[1] (North Central Ohio site) were used for testing the drain flow and runoff predictions of the WEPP-WTM model. The same three years data were used in Chapter 4 were used in this evaluation. As in Chapter 4, WEPP-WTM was run for the mean of two replications because the same rainfall and irrigation water for both replications was used in the weather input file of the model. Since there were no continuous water table depth measurements at this site, water table depth predictions of the model were tested and evaluated against a five year field data set from Aurora, North Carolina[2] (Skaggs, 1978).

6.2.1.1 North Central Ohio Site

The description of this site relevant to the data used in this chapter was given in Chapter 2. Detailed information about the site, field data measurements, hydrologic and crop results can be found in Schwab et al. (1963, 1975, and 1985).

6.2.1.2 Aurora, North Carolina Site

This 2 ha (5 ac) field site is located on the H. Carroll Austin farm near Aurora, North Carolina, and was described by Skaggs (1978). The schematic of experiment setup from Skaggs (1978) is given in Appendix M. The site consisted of three subsurface drained plots. The

---

[1] : The data from this site were also used to evaluate DRAINMOD (Skaggs, 1978) for North Central Ohio conditions by Skaggs et al. (1981) and to evaluate the ADAPT model (Chung et al., 1992).

[2] : The data from this site were previously used to evaluate DRAINMOD (Skagss, 1978 and 1982), ADAPT (Desmond et al., 1995), SWATREN (Workman and Skaggs, 1989), and PREFLO (Workman and Skaggs, 1990) models.

subsurface drain spacings on these plots were 7.5, 15, and 30 m (24.6, 49.2, and 98.4 ft), and the depth of the drains were 80, 90, and 100 cm (31.5, 35.5, and 39.4 in), respectively. The drains were 10 cm (4 in) diameter clay tile. Four lateral drains were installed on each plot. For most of the experimental period, the system was managed in conventional drainage mode, however, in some years, subirrigation was used to control the water table during April-July to grow potatoes and corn. The drain flows from the laterals and runoff from the plots were discharged into a 10 cm (4 in) corrugated plastic submain from which the plot water table was controlled during subirrigation. Continuous water table depths on each plot at this site were measured at the midspace of the subsurface drains using Leupold and Stevens type water level recorders (Skaggs, 1978).

6.2.2 Model Input Data

6.2.2.1 Weather data

The weather input file for both sites were prepared in hourly breakpoint form in the WEPP weather input file. The same hourly precipitation and daily maximum and minimum temperatures recorded at the North Central Ohio site and as used in Chapters 2 and 4 were used here as well. The same daily solar radiation, wind direction and speed, and dew point temperature data[3] as used in Chapter 4 were also used here.

Rainfall was recorded at the Aurora site, and daily maximum and minimum temperatures were measured at the Aurora weather station. The same evaporation pan data as used by Skaggs (1978) were used in place of daily PET calculations in WEPP-WTM. The PET input file for the year of 1974 is given in Appendix N.

6.2.2.2 Soil Data

The predominant soil type (about 80% of areal coverage) at the North Central Ohio site was Toledo silty clay. The same soil profile details as used in Chapters 2 and 4 were used here as well. The horizontal saturated hydraulic conductivity values were the same as those described in Chapter 2 (Table 2.4 and 2.11). The WEPP-WTM model was run with both constant and adjusted van Schilfgaarde equation estimated K_{sat} values.

To calculate the water table depth versus upward flux relationships and infiltration parameters, WEPP-WTM uses vertical saturated hydraulic conductivity values usually obtained using standard 7.6 cm (3 in) diameter soil cores. For this evaluation, vertical saturated hydraulic conductivity values for Toledo silty clay soil layers were obtained from Schwab et al. (1963) (Appendix C, Table A1). Soil water retention data for the Toledo silty clay were obtained from Skaggs et al. (1981) (Appendix A, Figure 1), Schwab et al. (1963) (Appendix C, Table A1), and field experiment notes. The soil water retention data for the three layers of Toledo silty clay are given in Table 6.1. In WEPP-WTM, these values were used to calculate water table depths versus drained volume relationships and unsaturated hydraulic conductivity values. Some other model soil input data such as albedo, baseline interrill and rill erodibility, critical shear, and baseline effective conductivity were calculated using the default WEPP equations given in the WEPP User Summary (Falanagan and Livingston, 1995). They are the same as previously given in Chapter 4 (Table 4.1).

At the Aurora site, the dominant soil type was Tomotly sandy loam with some Myatt sandy loam and Torhunta sandy loam in the areas of the 7.5 and 15 m (24.6 and 49.2 ft) spacings. The restrictive layers for the 7.5, 15, and 30 m (24.6, 49.2, and 98.4 ft) drain spaced plots were at the soil depths of 130, 140, and 170 cm (51.2, 55.1, and 66.9 ft), respectively. These depths were calculated by summing the drain depths and the depths from drains to restrictive layers as given by Skaggs (1978) (Appendix P, Table 8). Based on the lateral saturated hydraulic conductivity values given by Skaggs (1978) (Appendix R, Table 11), the soil profile was divided into 2 layers. The corresponding conductivity values for these layers, 1.0 and 3.0 cm/hr (0.4 and 1.2 in/hr), were obtained using the drawdown and auger hole methods (Skaggs, 1978). As mentioned earlier, core method measured vertical saturated hydraulic conductivity values in WEPP-WTM are important to calculate upward fluxes. These conductivity values could not be obtained for Aurora site, and they were not used in the previous model tests. However, upward fluxes with the corresponding water table depths for the Tomotly soil are given by Skaggs (1978) (Appendix S, Figure 25). Skaggs stated that these upward flux values were calculated by numerically solving the Richards equation (Richards, 1931). In WEPP-WTM, these upward flux values with their corresponding water table depths (Table 6.2) were used as input data in the soil input file. Therefore, the model upward flux routines were not tested for the Aurora site. For other vertical saturated hydraulic conductivity related calculations in the model, one half of the lateral saturated hydraulic conductivity value of the first layer was used. The soil water retention data for a 60 cm (23.6 in) depth of soil profile of Tomotly sandy clay (Lumbee s. l.) as given by Skaggs (1978) (Appendix O, Table 12) were used for both of the soil layers. These data are presented in Table

---

[3]: Illinois State Water Survey, 2204 Griffith Drive, Champaign, IL 61820-7495.

	Soil water pressure (cm of water)														
Soil	0	-10	-20	-40	-50	-60	-70	-80	-100	-150	-200	-330	-500	-1000	-15000
Toledo silty clay															
(0-0.2 m)	0.54	-	0.47	-	-	0.46	-	-	-	-	-	0.43	-	0.37	0.22
(0.2-0.5m)	0.49	-	0.47	-	-	0.46	-	-	-	-	-	0.43	-	0.39	0.24
(0.5-1.65m)	0.47	-	0.46	-	-	0.45	-	-	-	-	-	0.43	-	0.39	0.24
Tomotly sandy loam															
(0-1.3 m)	0.34	0.33	0.30	0.29	0.28	0.27	0.26	0.26	0.25	0.21	0.19	-	-	-	0.12

Table 6.1. Soil water retention data used in WEPP-WTM for Toledo silty clay at the North Central Ohio site and Tomotly sandy loam at the Aurora, North Carolina site. The Toledo silty clay data were obtained from Skaggs et al. (1981) (Appendix A, Figure 1), Schwab et al. (1963) (Appendix C, Table A1), and field experiment notes. The Tomotly sandy loam data were obtained from Skaggs (1978) (Appendix O, Table 12).

Water Table Depth (cm)	Upward Flux (cm/hr)
0	0.10420
10	0.08330
20	0.06670
30	0.05830
40	0.03960
50	0.01880
60	0.00640
70	0.00304
80	0.00221
90	0.00138
100	0.00113
110	0.00054
120	0.00004
150	0.0

Table 6.2. Water table depth versus upward flux relationships for Tomotly sandy loam at the Aurora, North Carolina site, obtained from Skaggs (1978) (Appendix S, Figure 25).

6.1. Some other soil input data at the Aurora site were obtained with the same methods used for Toledo silty clay (default WEPP equations).

6.2.2.3 Slope data

At the North Central Ohio site, the combination plots were surface drained at a 0.2% slope, and therefore a constant 0.2% slope value was used for these simulations. The profile width and length of the overland flow elements were chosen as equal to the plot width (37 m; 121 ft) and length (61 m; 200 ft), respectively. A constant 0.5% slope value was used for the simulations at the Aurora site. This value was obtained from one of the input file used in the ADAPT evaluation for the Aurora site by Desmond et al. (1995). The widths of the plots having drain spacings of 7.5, 15, and 30 m (24.6, 49.2, and 98.4 ft), are 30, 60, and 120 m (98.4, 196.8, and 393.7 ft), respectively. These numbers were obtained by multiplying the drain spacings by four (four laterals per plot). The length of the overland flow element was calculated as 60 m (197 ft) from the schematic given in Appendix M.

6.2.2.4 Plant/Management Input Data

Corn was grown at the North Central Ohio site during the three test years. The same plant/management input files used in Chapter 4 to test the hydrology component of the WEPP hillslope model were used in this chapter. As mentioned in Chapter 4, plant parameters for corn were obtained from the WEPP validation input data set files[4]. Field operations, dates, and additional input data were obtained from the experiment field notes and from Fausey (1999). The major difference between the plant/management input files used in Chapter 4 and those used in this chapter is in the drainage section. The drainage section of the plant/management input file of WEPP-WTM model includes the water table management option, drain pipe effective radius, Kirkham's equation depth (STORRO), and initial water table depth. The same values of these parameters used for DRAINMOD in Chapter 2 were used here. The planting and harvesting dates and drainage system parameters for this site are given in Table 6.3 and 6.4, respectively.

The crops grown at the Aurora site, and their planting and harvesting dates are also given in Table 6.3. These values were obtained from Skaggs (1978) (Appendix T, Table 9). For the crops grown at the Aurora site, plant parameters were also obtained from the WEPP validation input data set files. The same field operations used in the WEPP validation tests for these crops

---

[4] : The USDA-ARS National Soil Erosion Research Laboratory maintains a website for WEPP. This site has a page called "Hillslope Validation Data" which contains parameter selection help and

North Central Ohio				Aurora, North Carolina			
Year	Crop	Plant Date	Harvest Date	Year	Crop	Plant Date	Harvest Date
1969	corn	5-31	11-6	1973	potato	3-10*	6-20
					soybean	7-17	11-14
1970	corn	5-5	10-2	1974	potato	3-10*	6-17
					soybean	7-10	11-27
1971	corn	4-24	10-19	1975	corn	4-21	9-10
					wheat	11-12	-
				1976	wheat	-	6-16
					soybean	6-17	11-17
				1977	corn	4-25	9-1*

*: Approximate dates for planting or harvest

Table 6.3. Crops grown at the test sites and their planting and harvesting dates. The North Central Ohio site data were obtained from the experiment field notes. The Aurora, North Carolina site data were obtained from Skaggs (1978) (Appendix T, Table 9).

Parameter	North Central Ohio	Aurora, North Carolina		
Drain type	concrete tile	clay tile		
Drain spacing (m)	12.20	7.50	15.00	30.00
Drain depth (m)	0.90	0.80	0.90	1.00
Drain diameter (cm)	10.00	10.00	10.00	10.00
Drainage coefficient (cm/day)	5.30	1.00	1.00	1.00
Effective drain radius (cm)	0.48	0.25	0.25	0.25
Kirkham's depth (cm)	0.11	0.40	0.40	0.40
Ditch bottom width (cm)	-	2.00	2.00	2.00
Ditch side slope (cm/cm)	-	0.10	0.10	0.10

Table 6.4. Drainage system parameters for the test sites. The North Central Ohio site data were obtained from Chapter 2 (Table 2.1). The Aurora, North Carolina site data were obtained from Skaggs (1978) (Appendix P, Table 8) and Desmond et al. (1995). The ditch parameters were suggested by Workman (1999).

---

hydrology validation results. (http://topsoil.nserl.purdue.edu/weppmain/wepp.html).

with assumed approximate dates were also used for the crops at this site. Drainage system parameters for this site are also given in Table 6.4. Most of these parameter values were obtained from Skaggs (1978) (Appendix P, Table 8), and some of them were taken from the ADAPT input files developed by Desmond et al. (1995). The weir setting depths with their respective dates were also obtained from one of the ADAPT input files. The ditch parameters for this site were suggested by Dr. Stephen R. Workman (1999).

6.2.3 Evaluation Procedure

The same evaluation procedures used in Chapter 2 and 4 were used in this chapter. For the test years at each site, the agreement between predicted and measured values was quantified on the basis of daily and cumulative average deviation (cm) using the following equation:

$$average-deviation = \sum_{i=1}^{n} |x_i - y_i| / n \qquad \text{6.1}$$

where: x_i is the predicted daily drain flow, runoff volume or water table depth; y_i is the measured daily drain flow, runoff volume or water table depth on day i; and n is the number of days in the test period (year). Equation 6.1 was also used to calculate the agreement between cumulative predicted and measured outflows. In this situation, x_i is the predicted cumulative drain flow or runoff volume; and y_i is the measured cumulative drain flow or runoff volume on day i. A standard error for the WEPP-WTM predicted and observed daily water table depths was calculated using the following equation:

$$s = \sqrt{\sum_{i=1}^{n} (x_i - y_i) / n} \qquad \text{6.2}$$

where the symbols are the same as defined above. The standard errors for WEPP-WTM were compared with those obtained by Desmond et al. (1995) for ADAPT (Chung et al., 1992), by Skaggs (1978 and 1982) and Workman and Skaggs (1991) for DRAINMOD (Skaggs, 1978), and by Workman and Skaggs (1989) for SWATREN (Feddes et al., 1978) for the Aurora site.

The analysis performed with WEPP-WTM using constant and adjusted van Schilfgaarde equation estimated K_{sat} values will be presented first, followed by a comparison of WEPP-WTM drain flow and runoff results with those shown previously in Chapters 2 and 4. Then water table depth simulation results from WEPP-WTM, DRAINMOD, ADAPT, and SWATREN will be presented.

6.3 RESULTS AND DISCUSSION

6.3.1 Drain Flow and Runoff

Average deviations between daily observed and predicted outflows using constant and adjusted van Schilfgaarde equation estimated K_{sat} values in WEPP-WTM are given in Table 6.5. Average deviations for daily and cumulative drain flows and runoff are given on the left and right sides of Table 6.5, respectively. The minimum average daily and cumulative deviations for each replication of each testing year were underlined. The observed values were obtained from the drainage experiment at the OARDC North Central Branch, near Sandusky, Ohio (North Central Ohio site) (Schwab et al., 1963; 1975; and 1985).

The use of adjusted K_{sat} values in WEPP-WTM decreased the daily average deviations in drain flows for 1970 and 1971. However, use of the adjusted K_{sat} values increased the daily average deviations for drain flows for 1969. Furthermore, the adjusted K_{sat} values increased the daily average deviations for runoff for all the replications of the test years, except for replication 4 in 1970. For the cumulative outflows, using the adjusted K_{sat} values in WEPP-WTM model decreased the average deviations for cumulative drain flows for all the three test years. However, using the adjusted K_{sat} values increased the average deviations for cumulative runoff for 1969 and 1971. Overall, adjusted K_{sat} values improved the drain flow prediction accuracy of WEPP-WTM model and worsened the runoff prediction accuracy of WEPP-WTM model. This is because of the water balance algorithms of the model. The results that follow were obtained using the constant K_{sat} values.

Outflow average deviations obtained from WEPP-WTM, WEPP and DRAINMOD simulations are given in Table 6.6 for years 1969, 1970, and 1971. The average deviation values for WEPP-WTM are the same as those given in Table 6.5, and those for WEPP and DRAINMOD were presented previously in Chapter 4 (Table 4.3). The results in Table 6.6 suggest that no one model provided the smallest deviation in outflows for all the replications for three years test period. However, the WEPP-WTM model produced the smallest daily drain flow deviation for ten of the twelve daily drain flow comparisons (83%). For runoff, DRAINMOD gave the smallest daily average deviation for seven of twelve comparisons (58%). For cumulative outflows, WEPP-WTM produced the smallest drain flow deviation for all replications in 1969 and 1970, and

		Daily Outflows				Cumulative Outflows			
		Drain Flow		Runoff		Drain Flow		Runoff	
Year	Replication	CvSEEK*	AvSEEK+	CvSEEK	AvSEEK	CvSEEK	AvSEEK	CvSEEK	AvSEEK
1969	1	0.055	0.058	0.046	0.052	0.86	1.68	4.40	5.21
	2	0.049	0.050	0.045	0.051	2.21	1.31	4.26	5.07
	3	0.041	0.042	0.065	0.075	4.43	3.78	4.27	5.45
	4	0.036	0.038	0.081	0.087	1.08	0.67	1.32	2.25
	Mean	0.045	0.047	0.059	0.066	2.14	1.86	3.56	4.49
1970	1	0.047	0.047	0.022	0.025	0.88	1.06	1.03	0.55
	2	0.036	0.036	0.028	0.030	2.20	1.83	1.43	0.85
	3	0.039	0.037	0.057	0.058	1.78	1.41	3.41	2.79
	4	0.045	0.041	0.081	0.081	1.12	0.82	5.99	5.36
	Mean	0.042	0.040	0.047	0.048	1.49	1.28	2.96	2.39
1971	1	0.032	0.031	0.031	0.034	0.43	0.71	2.40	2.77
	2	0.017	0.018	0.029	0.032	0.83	0.48	1.84	2.19
	3	0.014	0.012	0.026	0.030	1.26	0.77	0.48	0.98
	4	0.018	0.014	0.022	0.026	2.08	1.59	0.19	0.64
	Mean	0.020	0.019	0.027	0.030	1.15	0.89	1.23	1.65

*: Using Constant van Schilfgaarde Equation Estimated K_{sat} values in WEPP-WTM

+: Using Adjusted van Schilfgaarde Equation Estimated K_{sat} values in WEPP-WTM

Table 6.5. Average deviations (cm) between daily and cumulative observed and WEPP-WTM (with constant van Schilfgaarde equation estimated K_{sat} and adjusted van Schilfgaarde equation estimated K_{sat}) predicted outflows for the North Central Ohio site.

		Daily Outflows						Cumulative Outflows					
		Drain Flow			Runoff			Drain Flow			Runoff		
Year	Replication	WEPP-WTM	WEPP	DRAIN-MOD	WEPP-WTM	WEPP	DRAIN-MOD	WEPP-WTM	WEPP	DRAIN-MOD	WEPP-WTM	WEPP	DRAIN-MOD
1969	1	0.055	0.358	0.047	0.046	0.081	0.022	0.86	42.70	1.58	4.40	9.21	2.50
	2	0.049	0.360	0.046	0.045	0.080	0.021	2.21	45.43	4.30	4.26	9.08	2.37
	3	0.041	0.307	0.043	0.065	0.089	0.029	4.43	35.97	5.73	4.27	8.05	0.37
	4	0.036	0.307	0.037	0.081	0.104	0.057	1.08	32.29	1.94	1.32	4.67	3.03
	Mean	0.045	0.333	0.043	0.059	0.088	0.032	2.14	39.10	3.39	3.56	7.75	2.07
1970	1	0.047	0.201	0.056	0.022	0.046	0.026	0.88	21.12	1.32	1.03	3.96	2.78
	2	0.036	0.213	0.043	0.028	0.042	0.030	2.20	23.77	3.84	1.43	3.46	3.28
	3	0.039	0.213	0.062	0.057	0.052	0.055	1.78	23.95	3.12	3.41	2.66	5.85
	4	0.045	0.222	0.058	0.081	0.069	0.079	1.12	23.15	2.32	5.99	1.16	8.43
	Mean	0.042	0.212	0.055	0.047	0.052	0.047	1.49	23.00	2.65	2.96	2.80	5.09
1971	1	0.032	0.114	0.039	0.031	0.062	0.013	0.43	13.45	1.26	2.40	3.04	0.41
	2	0.017	0.122	0.017	0.029	0.061	0.021	0.83	14.46	0.35	1.84	2.58	0.99
	3	0.014	0.111	0.019	0.026	0.062	0.022	1.26	12.86	0.43	0.48	1.95	2.36
	4	0.018	0.112	0.021	0.022	0.058	0.025	2.08	13.66	1.21	0.19	1.67	2.70
	Mean	0.020	0.115	0.024	0.027	0.061	0.020	1.15	13.61	0.81	1.23	2.31	1.62

Table 6.6. Average deviations (cm) between daily and cumulative observed and WEPP-WTM, WEPP and DRAINMOD predicted outflows for North Central Ohio site for 1969, 1970, and 1971. Baseline effective conductivity was used in WEPP, and constant van Schilfgaarde equation estimated K_{sat} values were used in both WEPP-WTM and DRAINMOD.

replication 1 in 1971 (75%) and the smallest runoff deviations in five of twelve comparisons (42%). Overall, WEPP-WTM drain flow predictions were better than those obtained with DRAINMOD and WEPP for 19 of 24 comparisons (79%). For runoff, however, predictions by DRAINMOD are better than those obtained from WEPP-WTM and WEPP in 50% of the comparisons.

Figures 6.1 through 6.3 illustrate daily drain flows predicted by WEPP-WTM for the years 1969 through 1971, respectively, compared to the measured drain flows. In these figures, the model simulation results were compared to the mean of the two replications where the same rainfall and irrigation data were valid for both replications. Predicted and measured drain flow depths and storm event times matched each other closely. These results show that WEPP-WTM did not consistently under or overpredict drain flow. Within the same year on some storm events, the model underpredicted and on other storm events the model overpredicted. However, the overall differences are not large. The only events where WEPP-WTM did not predict any drain flow were on days 111 and 121 in 1970 (Fig. 6.2). These measured drain flows are relatively small and may have resulted because of preferential flows through large cracks during the hot summer months. In Chapter 2, DRAINMOD also did not predict these drain flows (not shown).

Figures 6.4 through 6.6 illustrate daily runoff predictions from WEPP-WTM for 1969, 1970, and 1971, respectively. The predicted values are again compared to the mean of the measured runoff depth from the two individual replicates (same rainfall and irrigation data). For 1969 (Fig. 6.4), WEPP-WTM predicted runoff on the same days on which runoff was measured, however, WEPP-WTM also overpredicted by 100% runoff for day 79 (small event), and by 14% on day 95 (large event). These results are similar to those from WEPP in Chapter 4 (Fig. 4.4). The worst WEPP-WTM runoff predictions were obtained in 1970 for replicates 3 and 4 (Fig. 6.5), where no runoff was predicted for six events. However, WEPP-WTM only underpredicted runof by 21 and 31% for days 66 and 79, respectively. DRAINMOD simulations in Chapter 2 also did not predict runoff for four events for these replications in this year (not shown). Furthermore, the runoff depths from the replications 1 and 2 are not large as those from the replications 3 and 4 for these events. For 1971 (Fig. 6.6), the model overpredicted runoff by 100, 83 and 46% on days 54, 71 and 90, respectively. However, these predictions still produced smaller daily average deviations than those produced by WEPP (Table 6.6).

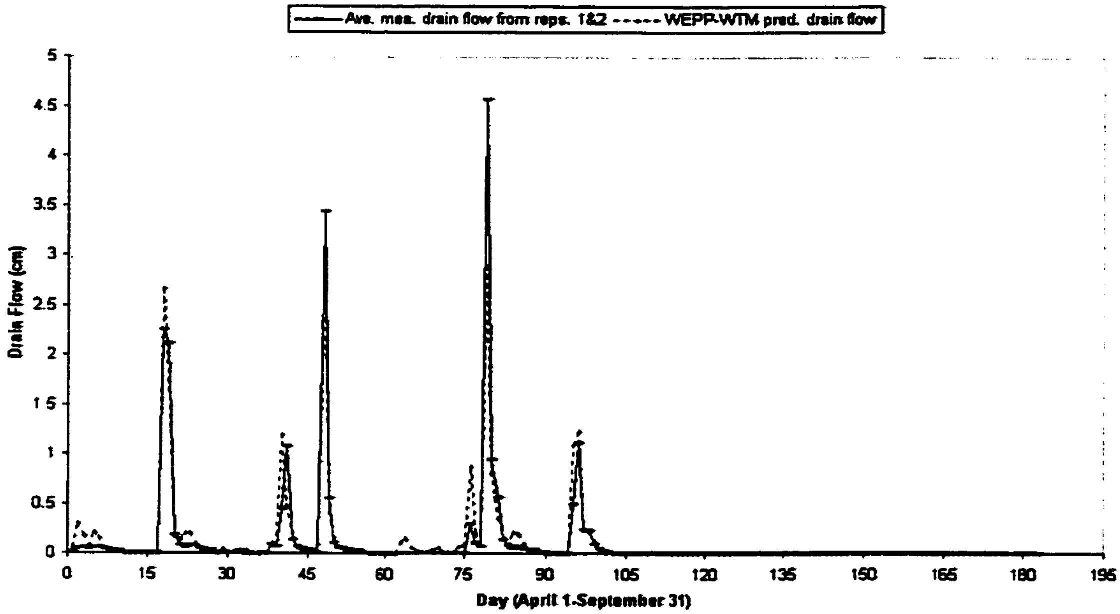

Figure 6.1. WEPP-WTM model predicted and average measured daily drain flows for the replications 1 and 2 at the North Central Ohio site during 1969.

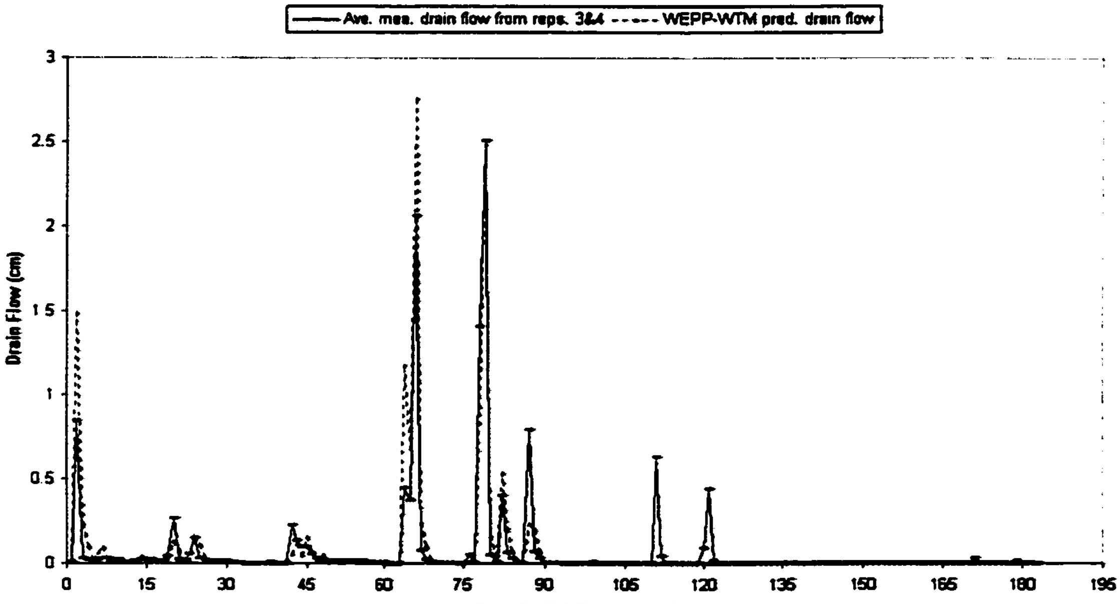

Figure 6.2. WEPP-WTM model predicted and average measured daily drain flows for the replications 3 and 4 at the North Central Ohio site during 1970.

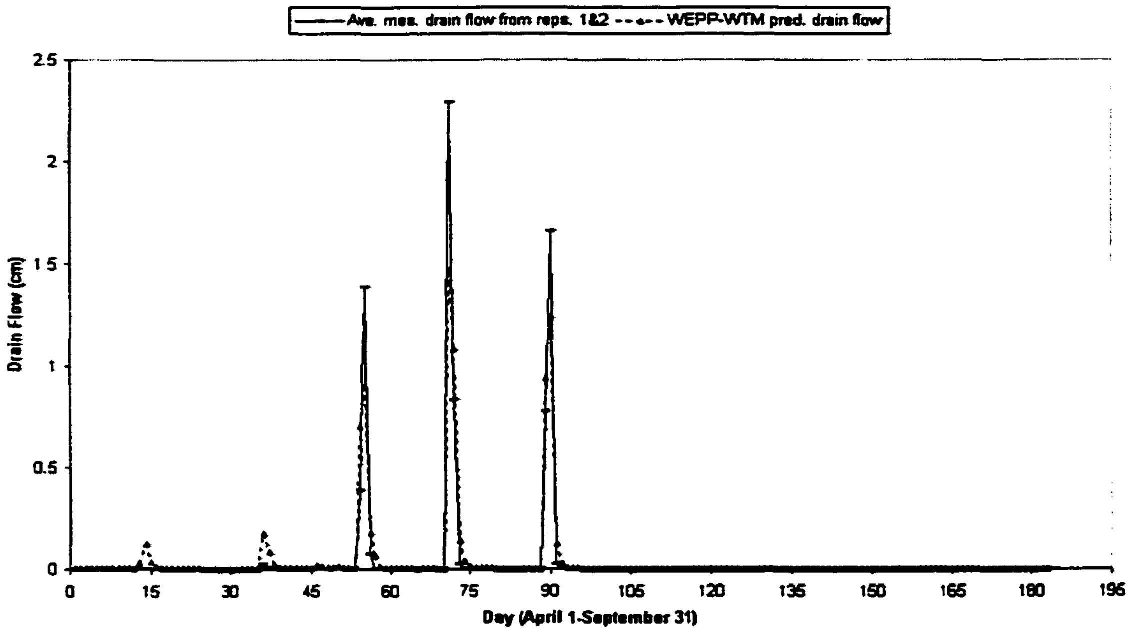

Figure 6.3. WEPP-WTM model predicted and average measured daily drain flows for the replications 1 and 2 at the North Central Ohio site during 1971.

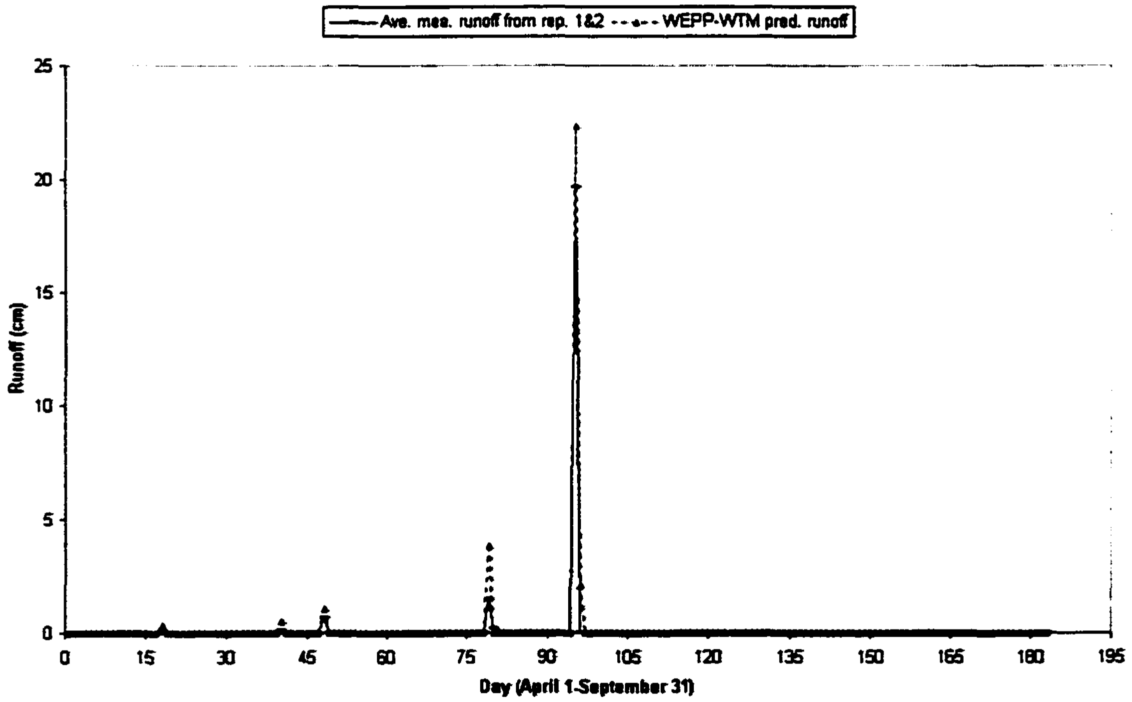

Figure 6.4. WEPP-WTM model predicted and average measured daily runoff depths for the replications 1 and 2 at the North Central Ohio site during 1969.

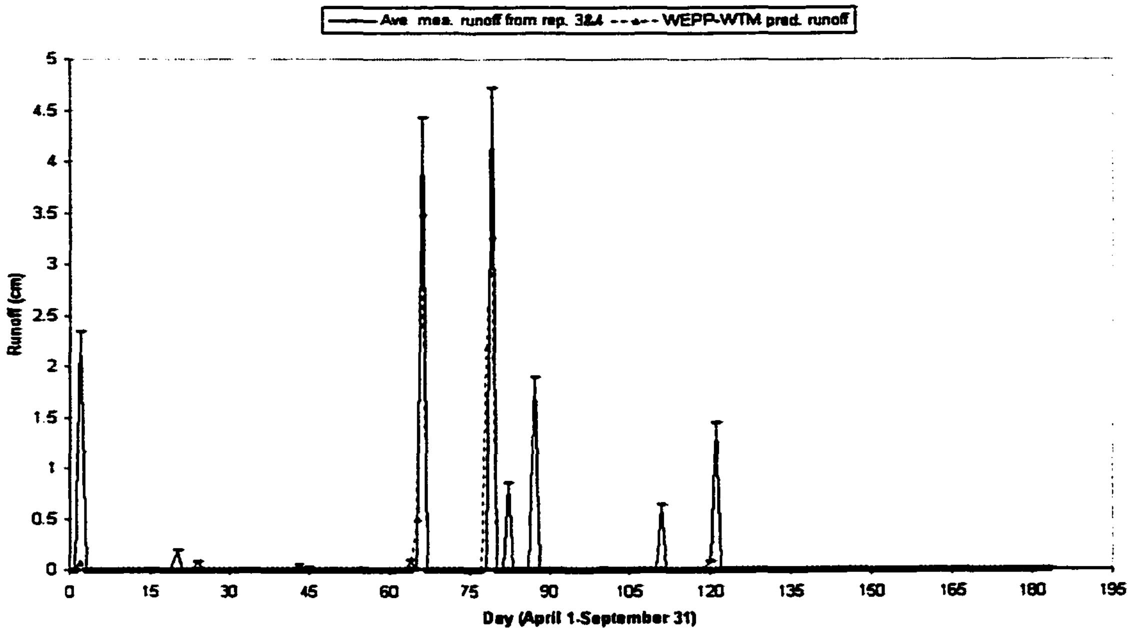

Figure 6.5. WEPP-WTM model predicted and average measured daily runoff depths for the replications 3 and 4 at the North Central Ohio site during 1970.

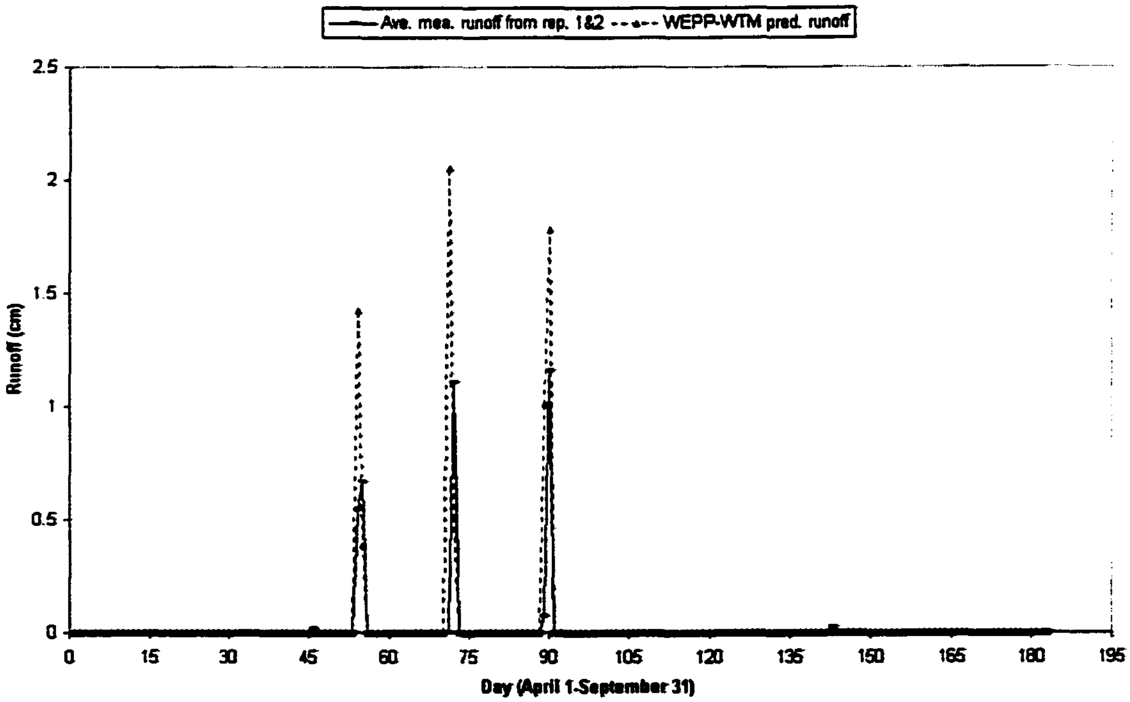

Figure 6.6. WEPP-WTM model predicted and average measured daily runoff depths for the replications 1 and 2 at the North Central Ohio site during 1971.

The cumulative drain flows are illustrated in Figures 6.7, 6.8, and 6.9 for years 1969, 1970, and 1971, respectively. These figures show how well the predicted cumulative drain flows match the measured cumulative drain flows. For 1969 and 1971 (Figs. 6.7 and 6.9), the predicted cumulative drain flows at the end of the evaluation season are between the cumulative values from the replications. The cumulative runoff depths are shown in Figures 6.10 through 6.12 where runoff was overpredicted for 1969 and 1971, and underpredicted for 1970. When we consider the runoff depths at the end of the evaluation season, the runoff depth differences between predicted and the average measured runoff depths of the replicate pairs are 7.9, 7.3, and 3.6 cm (3.1, 2.9, and 1.4 in) for the years 1969, 1970, and 1971, respectively. These runoff depth differences correspond to 35.5, 43.4, and 100% of the average measured runoff depths from the replicate pairs.

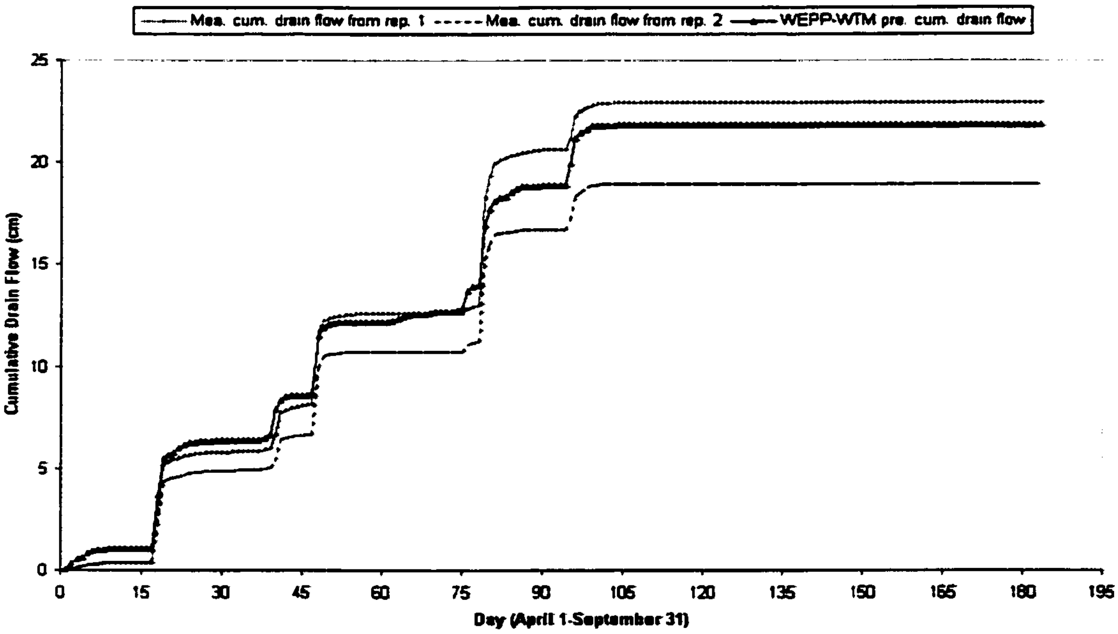

Figure 6.7. WEPP-WTM model predicted and measured cumulative drain flows for the replications 1 and 2 at the North Central Ohio site during 1969.

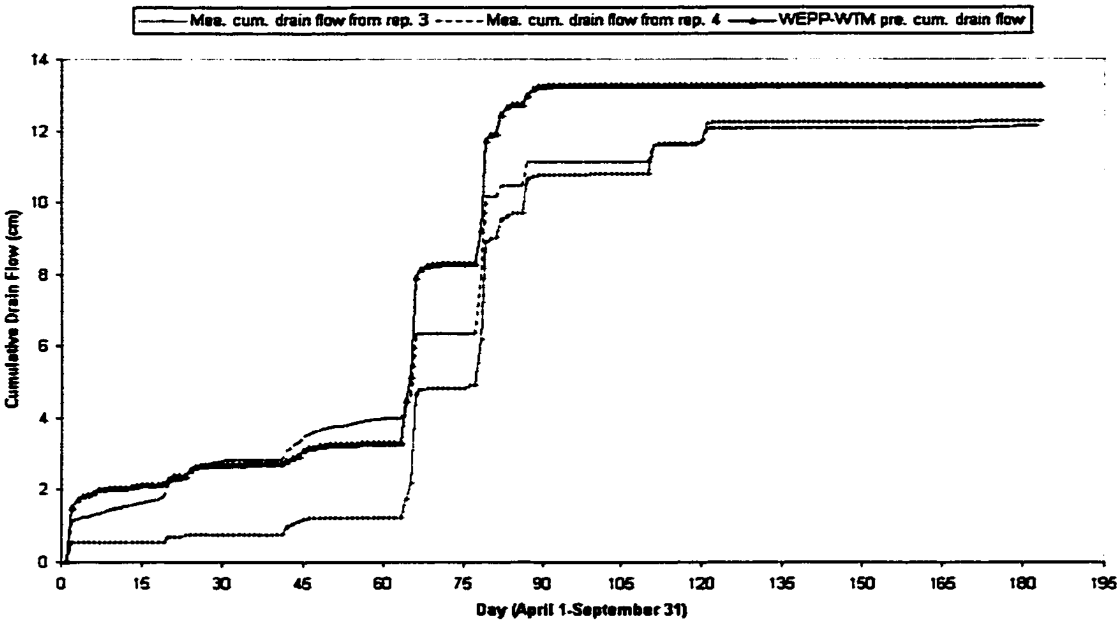

Figure 6.8. WEPP-WTM model predicted and measured cumulative drain flows for the replications 3 and 4 at the North Central Ohio site during 1970.

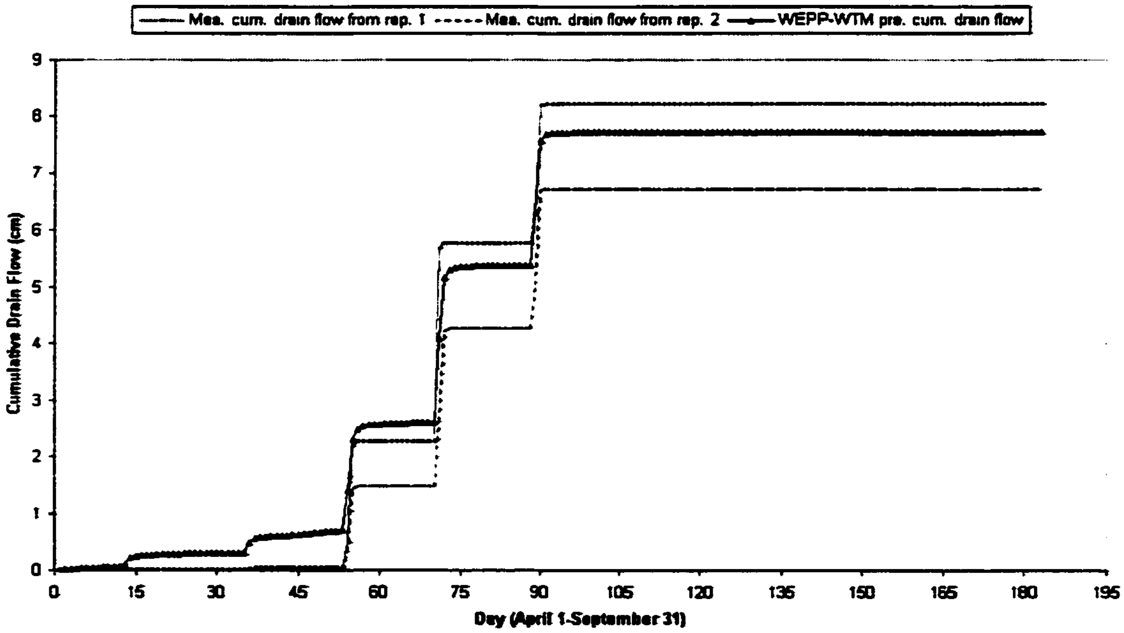

Figure 6.9. WEPP-WTM model predicted and measured cumulative drain flows for the replications 1 and 2 at the North Central Ohio site during 1971.

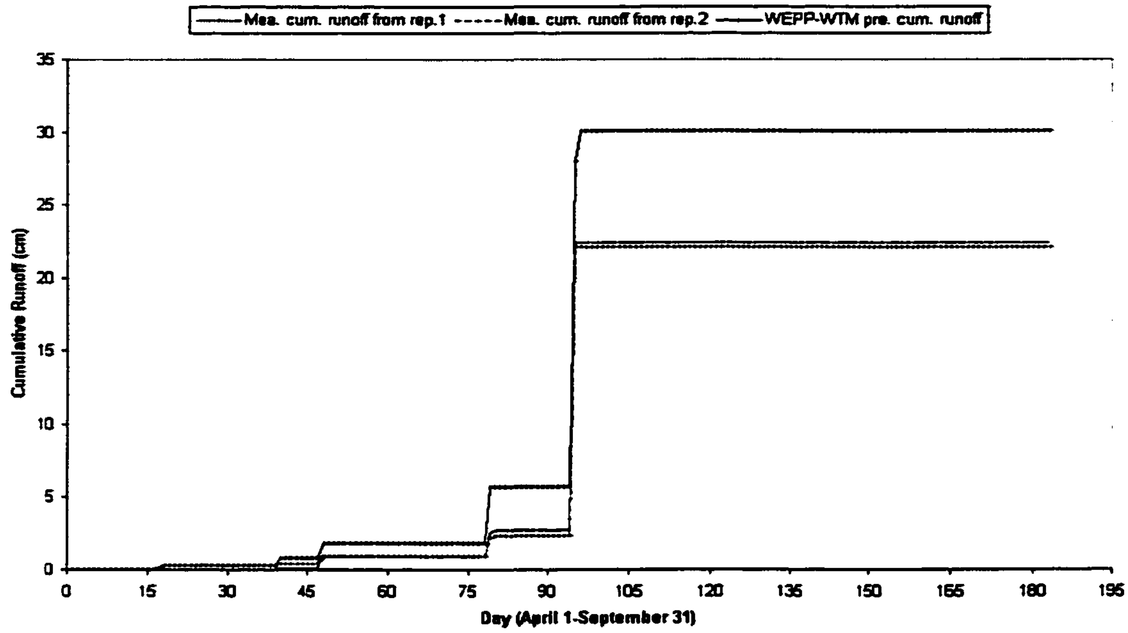

Figure 6.10. WEPP-WTM model predicted and measured cumulative runoff depths for the replications 1 and 2 at the North Central Ohio site during 1969.

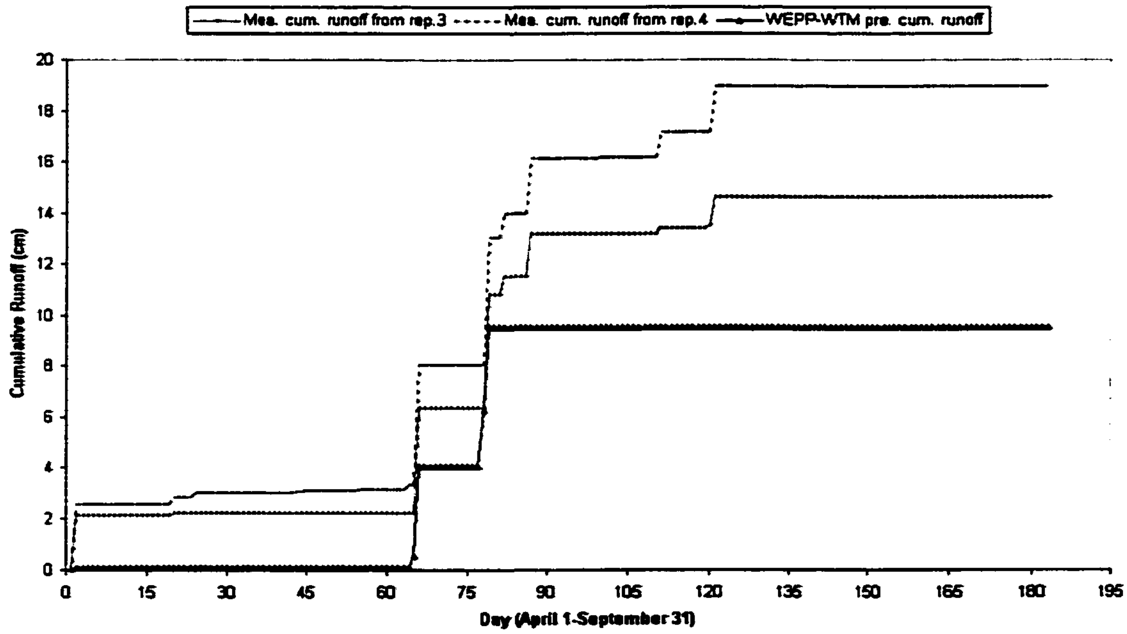

Figure 6.11. WEPP-WTM model predicted and measured cumulative runoff depths for the replications 3 and 4 at the North Central Ohio site during 1970.

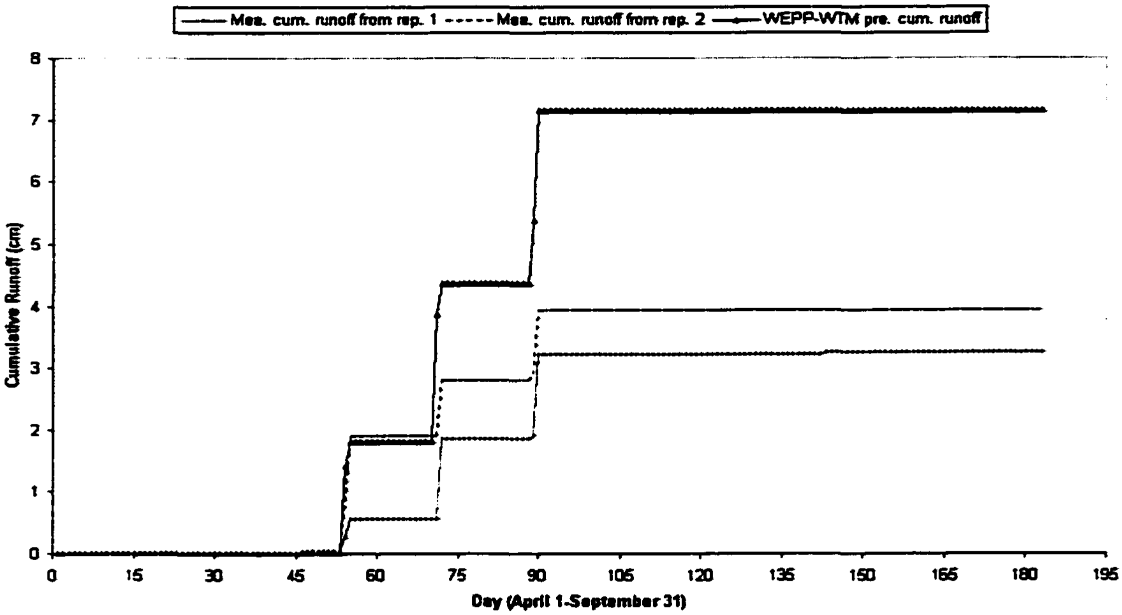

Figure 6.12. WEPP-WTM model predicted and measured cumulative runoff depths for the replications 1 and 2 at the North Central Ohio site during 1971.

6.3.2 Water Table Depths

Measured and predicted daily water table depths with weir depths were evaluated for the three drain spacings and the five years of observations at the Aurora site. The calculated standard errors and average deviations between measured and WEPP-WTM predicted daily water table depths are given in Table 6.7. The overall best predictions were obtained in 1977. If the standard errors are considered alone, the poorest predictions were obtained in 1976, 1973, and 1975 within the drain spacings of 7.5, 15, and 30 m, respectively. When average deviations are considered alone, WEPP-WTM simulations produced the poorest water table depths in 1976, 1974, and 1975 within the drain spacings of 7.5, 15, and 30 m, respectively.

For discussion purposes, the results for 1973 and 1977 are presented in Figures 6.13 to 6.18. The weir depths indicate periods of free drainage and where subirrigation were employed. For free drainage, the weir was set at 80, 90, and 100 cm (31.5, 35.4, and 39.4 in) for the drain spacings of 7.5, 15, and 30 m (24.6, 49.2, and 98.4 ft), respectively. In Figures 6.13 through 6.18, WEPP-WTM predicted changes in water table depths that matched the timing of weir depth

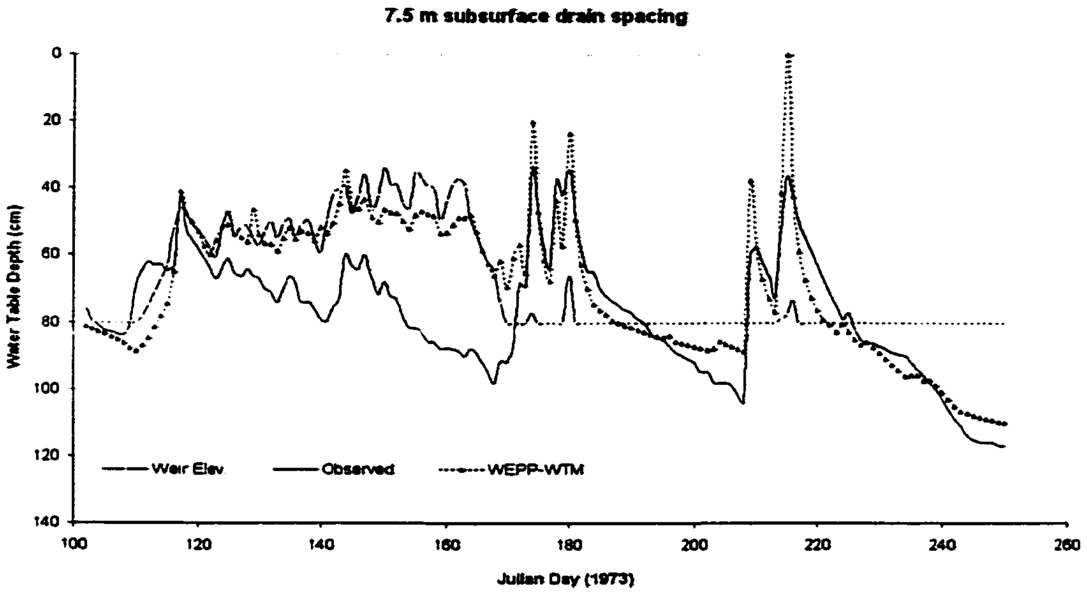

Figure 6.13. Observed and WEPP-WTMM predicted daily water table depths at the midspace of drains spaced 7.5 m apart on the Aurora site during 1973.

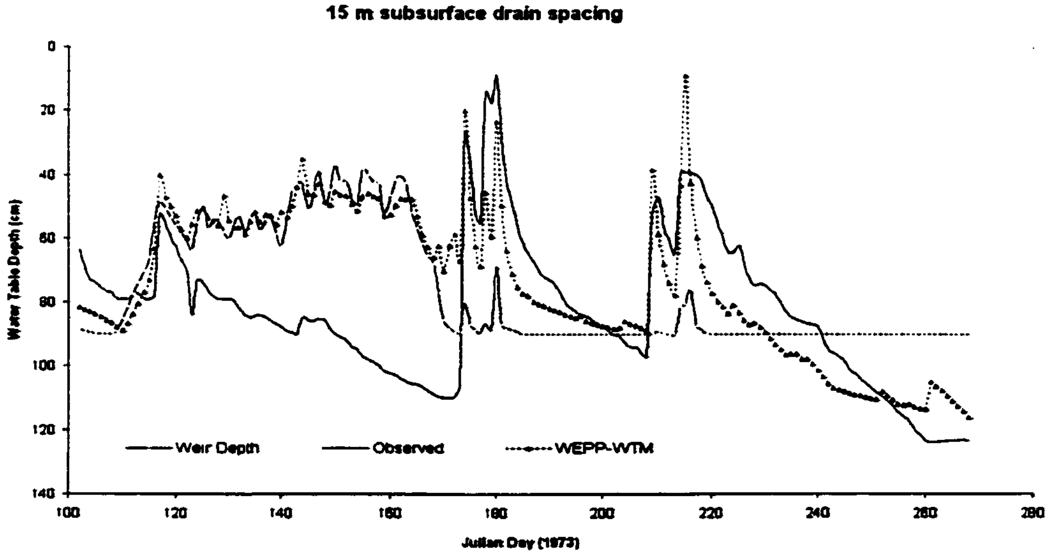

Figure 6.14. Observed and WEPP-WTMM predicted daily water table depths at the midspace of drains spaced 15 m apart on the Aurora site during 1973.

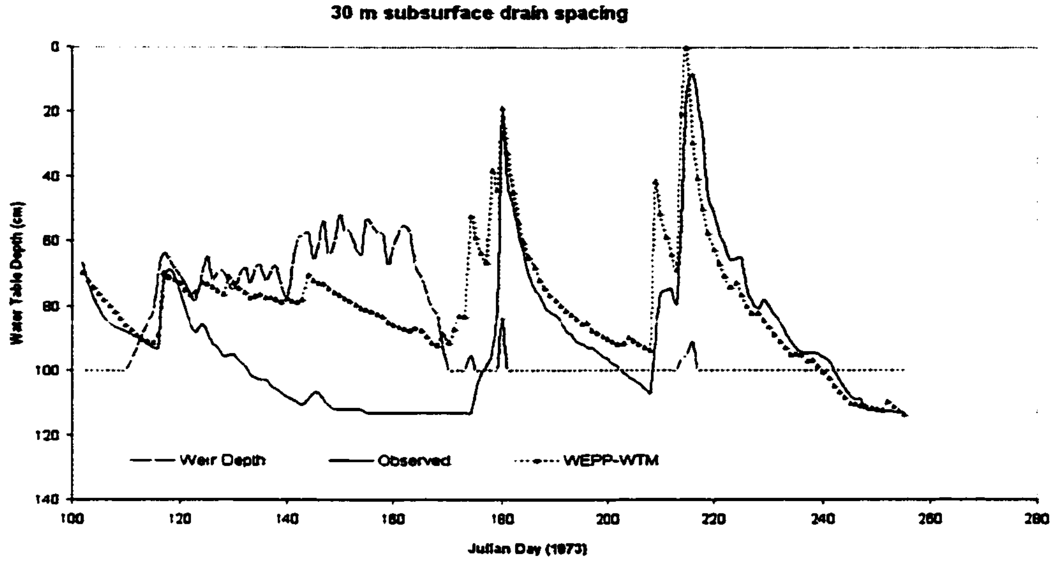

Figure 6.15. Observed and WEPP-WTMM predicted daily water table depths at the midspace of drains spaced 30 m apart on the Aurora site during 1973.

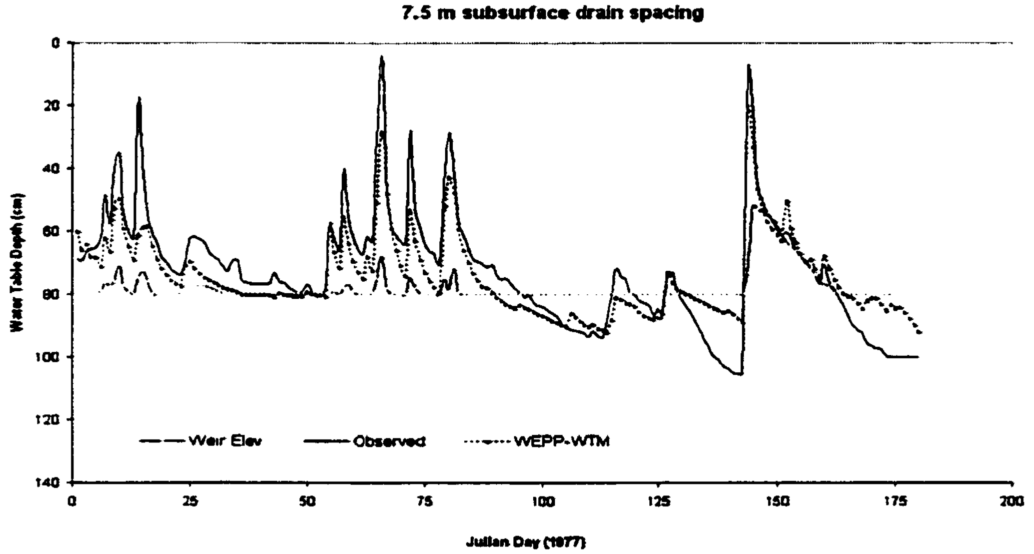

Figure 6.16. Observed and WEPP-WTM predicted daily water table depths at the midspace of drains spaced 7.5 m apart on the Aurora site during 1977.

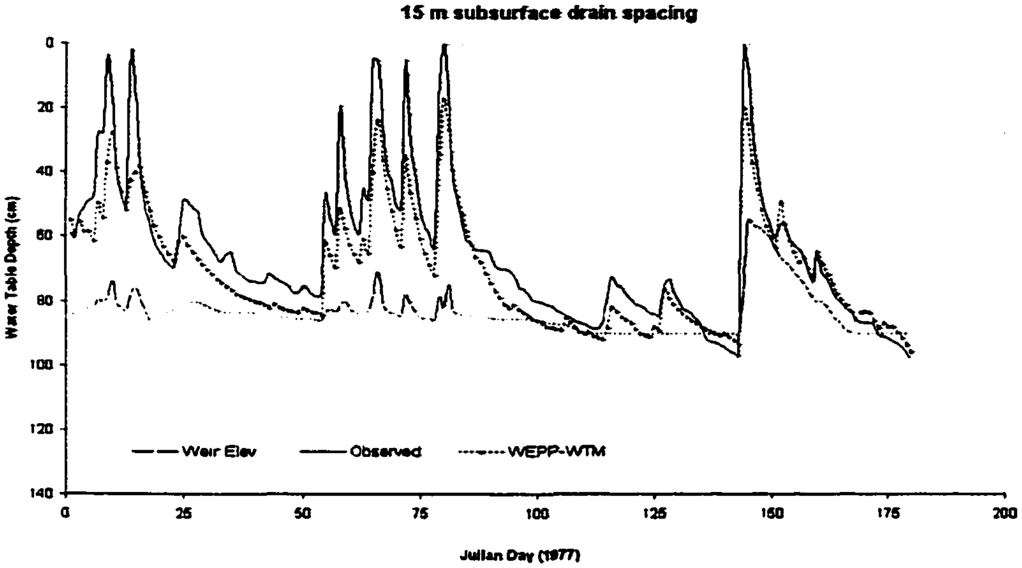

Figure 6.17. Observed and WEPP-WTM predicted daily water table depths at the midspace of drains spaced 15 m apart on the Aurora site during 1977.

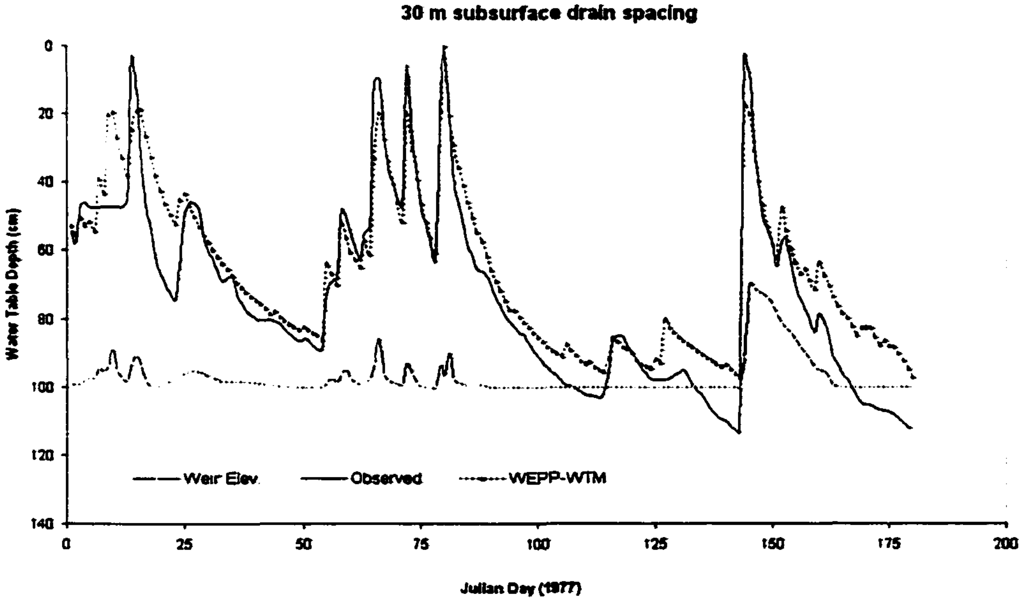

Figure 6.18. Observed and WEPP-WTM predicted daily water table depths at the midspace of drains spaced 30 m apart on the Aurora site during 1977.

	Drain Spacing (m)					
	7.5		15		30	
Year	s	a.d.	s	a.d.	s	a.d.
1973	16.55	12.39	25.18	18.92	20.07	15.04
1974	13.76	11.78	23.05	19.78	18.84	15.15
1975	13.45	10.45	20.56	17.60	21.98	15.94
1976	20.71	16.24	24.08	18.96	19.56	13.98
1977	8.96	6.89	9.73	7.12	11.27	8.89

Table 6.7. Standard errors (s) (cm) and average deviations (a.d.) (cm) between observed and WEPP-WTM predicted water table depths for Aurora, North Carolina site.

changes, and in most cases the water table depth response was similar to that observed. However, the model predicted absolute water table depths much better in 1977 compared to 1973 (also see Table 6.7).

For example in 1973, there is subirrigation for the days between 120 and 170. The model predicted water table depths that tracked the weir depths for these days very well. This is normally expected from a subirrigation system if the system is operated properly and it worked as simulated in the model. However, when the observed water table depths are considered during these days, it appears that there is no subirrigation application or subirrigation flux rates were not large enough to keep the water table at the weir setting depths. Similar results were obtained from DRAINMOD (Skaggs, 1978) for this year. However, the magnitudes of differences between the predicted and observed water table depths for these days are a little larger for WEPP-WTM compared to DRAINMOD (not shown). One of the possible reasons is the hourly time step used in the water balance routines of WEPP-WTM. As mentioned in Skaggs (1978), one of the weaknesses of DRAINMOD, as now WEPP-WTM, is that when subirrigation is used in these models, the midspace water table depth response of the model is immediate. However, Skaggs (1978) stated that this probably does not happen in real field conditions, and that there is a time lag between a rise in the ditch water level and midspace water table response. This may be particularly true when subirrigation is initiated when the water table is very low and thus the soil conditions are dry. This was observed in 1975 (not shown) for the 15 and 30 m (49.2 and 98.4 ft) drain spacings. The overall best predictions were obtained in 1977 (Figs. 6.16, 6.17, and 6.18) in which the systems were primarily in free drainage mode, and when the weir was raised the magnitude of the weir depth change and the duration of subirrigation were much less than those seen in 1973.

WEPP-WTM water table depth standard errors were compared with those obtained using DRAINMOD by Skaggs (1978 and 1982) and Workman and Skaggs (1991), ADAPT by Desmond et al.(1995), and SWATREN by Workman and Skaggs (1989) for the same site. The standard error of estimated water table depths are presented in Figures 6.19, 6.20, and 6.21 for the 7.5, 15, and 30 m drain spacings, respectively. DRAINMOD 1 results were obtained using the field measured water table depth versus drainage volume relationship. For DRAINMOD 2, the water table depth versus drainage volume relationship was estimated using the soil water characteristics. For ADAPT 1, the standard errors were obtained when the upward flux upper limit datum point was at the soil surface, and for ADAPT 2 the standard errors were obtained when the upward flux upper limit datum point was at one half the root zone depth. It should be noted that except for DRAINMOD 1 simulations, the water table depth versus drainage volume relationship was estimated.

From Figures 6.19, 6.20, and 6.21, it is clear that WEPP-WTM gave results similar to those of the other models. Within each spacing, the average standard error over all five years with WEPP-WTM was larger than those for DRAINMOD 1 simulations. However, the WEPP-WTM average standard error was very close to those from DRAINMOD 2, SWATREN, ADAPT 1 and 2 for 7.5 m drain spacing, was larger than the others for 15 m drain spacing, and was less than the others for the 30 m drain spacing. The ranked overall mean of the standard errors for all three drain spacings from the DRAINMOD 1, ADAPT 1, DRAINMOD 2, ADAPT 2, WEPP-WTM, and SWATREN water table depth predictions are 14.65, 16.87, 17.27, 17.47, 17.85, and 18.42 cm (5.77, 6.64, 6.80, 6.88, 7.03, and 7.25 in), respectively. The overall mean of the average deviations from all the models except DRAINMOD 1 is 14 cm (5.5 in). For DRAINMOD 1, an average deviation of 11.4 cm (4.5 in) was calculated from the values given in by Skaggs (1978 and 1982). Workman and Skaggs (1991) stated that DRAINMOD 1 gave better results because field measured drained volume versus water table depth data were used.

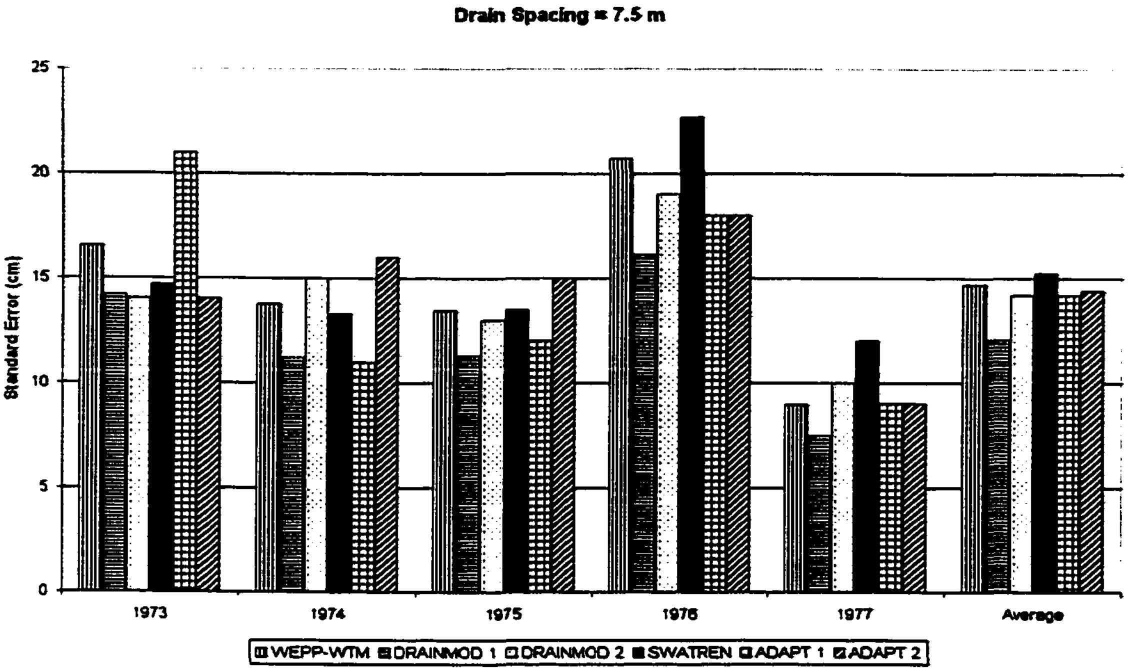

Figure 6.19. Standard errors of estimated water table depth means by four water table management models under 7.5 m drain spacing for the Aurora, North Carolina site.

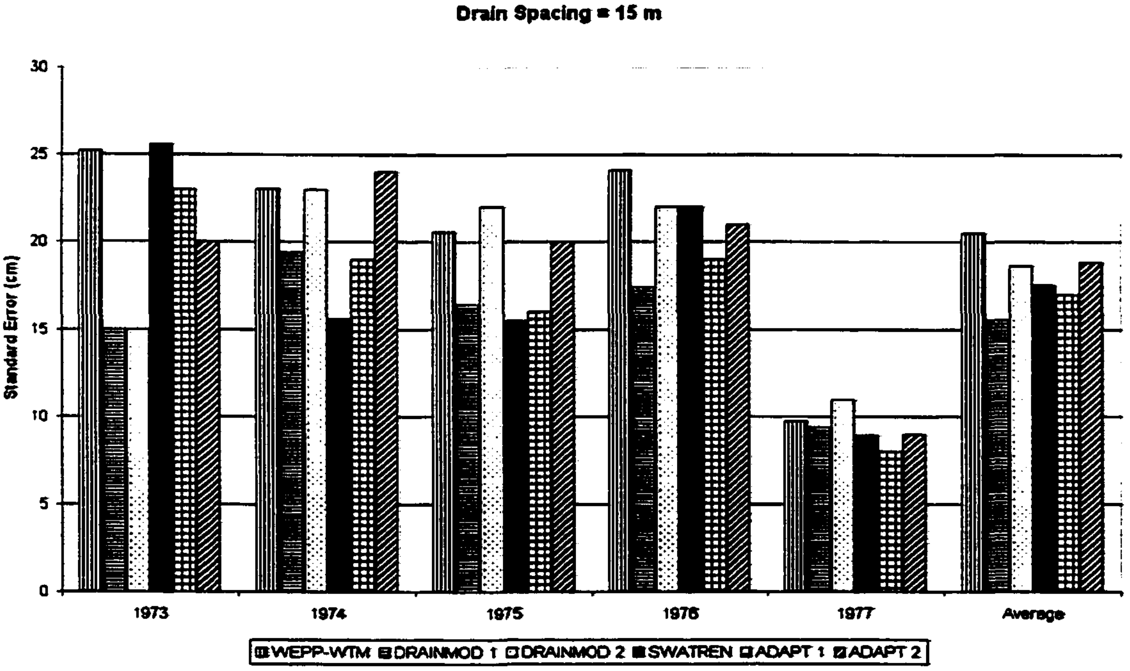

Figure 6.20. Standard errors of estimated water table depth means by four water table management models under 15 m drain spacing for the Aurora, North Carolina site.

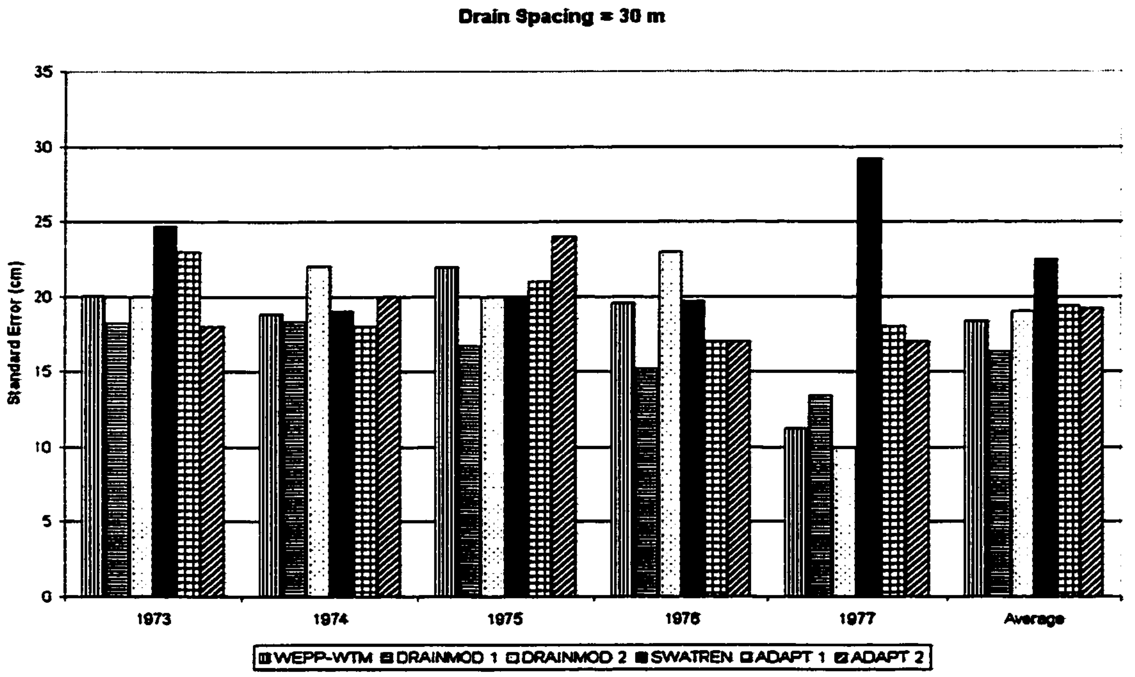

Figure 6.21. Standard errors of estimated water table depth means by four water table management models under 30 m drain spacing for the Aurora, North Carolina site.

6.4 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The purpose of the work presented in this chapter was to evaluate the performance of the Water Erosion Prediction Project-Water Table Management (WEPP-WTM) model in simulating runoff, drain flow, and water table depth for subsurface drained cropland conditions. The runoff, drain flow, and daily water table depth prediction accuracy of WEPP-WTM for field sized areas was tested against field measured data from two sites. Three years (1969, 1970, and 1971) of field data obtained from the combination plots (surface and subsurface drained) of the drainage experiment of Schwab et al. (1963; 1975; and 1985) at the Ohio Agricultural Research and Development Center (OARDC) North Central Branch, near Sandusky, Ohio (North Central Ohio site) were used for testing the drain flow and runoff predictions of WEPP-WTM. There were no continuous water table depth measurements at the OARDC site. Water table depth predictions of the model were evaluated against a five year field data set from Aurora, North Carolina (Skaggs, 1978).

The analysis of WEPP-WTM using constant and adjusted van Schilfgaarde equation estimated K_{sat} values indicated that using the adjusted saturated horizontal hydraulic conductivity (K_{sat}) values generally improved the drain flow prediction accuracy of the model while it decreased the runoff prediction accuracy of the model.

As would be expected, overall WEPP-WTM produced drain flow and runoff results similar to those from DRAINMOD. The WEPP-WTM model produced average deviations for drain flow that were better than all of those obtained with WEPP and in most cases better than those obtained with DRAINMOD. However, runoff predictions from WEPP-WTM were similar, but poorer than those obtained from DRAINMOD, but much better than those from WEPP.

To evaluate the water table depth prediction accuracy of WEPP-WTM, the models predicted standard errors were compared with those obtained from published results using DRAINMOD, ADAPT, and SWATREN for the Aurora, North Carolina site. Overall, the predictions of water table depth from WEPP-WTM were very comparable to those from the other models. The ranked overall mean of the standard errors for all three drain spacings from the DRAINMOD 1, ADAPT 1, DRAINMOD 2, ADAPT 2, WEPP-WTM, and SWATREN water table depth predictions are 14.65, 16.87, 17.27, 17.47, 17.85, and 18.42 cm (5.77, 6.64, 6.80, 6.88, 7.03, and 7.25 in), respectively. The overall mean of the average deviations from all the models except DRAINMOD 1 is 14 cm (5.5 in). For DRAINMOD 1, an average deviation of 11.4 cm (4.5 in) was calculated from the values given in by Skaggs (1978 and 1982).

The runoff related sediment yield prediction capability of WEPP-WTM was not tested, and therefore, testing this component is needed.

For this evaluation, WEPP-WTM was tested against data from individual plots and field sized areas. The WEPP watershed model (Ascough II et al., 1997) should now be evaluated for watershed scale capability after WEPP-WTM model is connected with it.

The WEPP-WTM model does not simulate preferential flow to the drains through cracks which can occur in clayey soils during hot summer months. Algorithms simulating preferential flow could be added to the model and evaluated, possibly on conditions similar to those evaluated by Workman and Skaggs (1990 and 1991) with PREFLO.

The WEPP-WTM model was developed for humid regions. For the possible use of the model for semi arid regions, the runoff prediction of the model for these regions should to be tested.

The time lag between a rise in the ditch water level (weir depth changes) and the midspace water table response may be a problem in modeling subirrigation. This time lag could possibly by evaluated using the HYDRUS-2D model (Simunek et al., 1996). The effect of the time lag could then be incorporated into the water table depth prediction algorithms of WEPP-WTM and tested.

WEPP-WTM has the ability to be applied to small watersheds when it is connected with the WEPP watershed model (Ascough II et al., 1997). The next chapter provides an evaluation of the WEPP watershed model with WEPP-WTM for a watershed with several components of water table management.

6.5 REFERENCES

Ascough II, J.C., C. Baffaut, M.A. Nearing and B.Y. Liu. 1997. The WEPP watershed model: I. Hydrology and erosion. Transactions of the ASAE 40(4):921-933.

Baffaut, C., M.A. Nearing, J.C. Ascough II and B.Y. Liu. 1997. The WEPP watershed model: II. Sensitivity analysis and discretization on small watersheds. Transactions of the ASAE 40(4):935-943.

Brown, L.C., A. Ward and N.R. Fausey. 1997. Agricultural water table management systems. Extension Fact Sheet AEX 321-97. The Ohio State University Extension, Columbus. 8 p.

Chung, S.O., A.D. Ward and C.W. Schalk. 1992. Evaluation of the hydrologic component of the ADAPT water table management model. Transactions of the ASAE 35(2):571-579.

Desmond, E.D., A.D. Ward, N.R. Fausey and S.R. Workman. 1995. Comparison of daily water table depth prediction by four simulation models. Transactions of the ASAE 39(1):111-118.

Fausey, N.R. 1999. Personal communication. Research leader, USDA-ARS Soil Drainage Research Unit, Columbus, Ohio.

Fausey, N.R., L.C. Brown, H.W. Belcher and R.S. Kanwar. 1995. Drainage and water quality in Great Lakes and Cornbelt States. J. Irrigation and Drainage Engineering, ASCE 121(4):283-288.

Feddes, R.A., P.J. Kowalik and H. Zaradyn. 1978. Simulation of field water use and crop yield. Simulation Monographs. Wageningen, the Netherlands: PUDOC.

Flanagan, D.C. and S.J. Livingston (Eds.). 1995. WEPP user summary. NSERL Report No. 11. USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, Indiana. 131 p.

Flanagan, D.C. and M.A. Nearing (Eds.). 1995. WEPP technical documentation. NSERL Report No. 10. USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, Indiana. 284 p.

Jensen, M.E. (Ed.). 1974. Consumptive use of water and irrigation requirements. Rep. Tech.

Com. on Irrig. Water Requirements, Irrig. and Drain. Div. ASCE. 227 pp.

Lane, L.J. and M.A. Nearing (Eds.). 1989. USDA-Water erosion prediction project: Hillslope profile model documentation. NSERL Rep. No. 2, USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, Indiana. 265 p.

Liu, B.Y., M.A. Nearing, C. Baffaut and J.C. Ascough II. 1997. The WEPP watershed model: III. Comparisons to measured data from small watersheds. Transactions of the ASAE 40(4):945-952.

Nearing, M.A., D.I. Page, J.R. Simanton and L.J. Lane. 1989. Determining erodibility parameters from rangeland field data for a process-based erosion model. Transactions of the ASAE 32(3):919-924.

Penman, H.L. 1963. Vegetation and Hydrology. Tech. Com. No. 53, Commonwealth Bureau of Sols, Harpenden, England. 125 p.

Richards, L.A. 1931. Capillary conduction of liquids through porous mediums. Physics 1(1):318-333.

Schwab, G.O., T.J. Thiel, G.S. Taylor and J.L. Fouss. 1963. Tile and surface drainage of clay soils. Research Bulletin 935. Ohio Agricultural Experiment Station, Wooster, Ohio. 47 p.

Schwab, G.O., N.R. Fausey and C.R. Weaver. 1975. Tile and surface drainage of clay soils. Research Bulletin 1081. Ohio Agricultural Research and Development Center, Wooster, Ohio. 37 p.

Schwab, G.O., N.R. Fausey, E.D. Desmond and J.R. Holman. 1985. Tile and surface drainage of clay soils. Research Bulletin 1166. Ohio Agricultural Research and Development Center, Wooster, Ohio. 29 p.

Simunek, J., M. Sejna and M. Th. van Genuchten. 1996. Ground water modeling software HYDRUS-2D. Simulating water flow and solute transport in two-dimensional variably saturated media. IGWMC-TPS 53. Ver. 1.0 U.S. Salinity Laboratory, USDA/ARS, Riverside, California. 167 p.

Skaggs, R.W. 1978. A water management model for shallow water table soils. Report No. 134. Raleigh, North Carolina. Water Resources Research Institute, Univ. of North Carolina. 175 p.

Skaggs, R.W., N.R. Fausey and B.H. Nolte. 1981. Water management model evaluation for North Central Ohio. Transactions of the ASAE 24(4):922-928.

Skaggs, R.W. 1982. Field evaluation of a water management simulation model. Transactions of the ASAE 25(3):666-674.

Van Schilfgaarde, J. 1963. Design of tile drainage for falling water tables. J. Irrigation and Drainage Engineering ASCE 89(IR2):1-11.

Workman, S.R. and R.W. Skaggs. 1989. Comparison of two drainage simulation models using field data. Transactions of the ASAE 32(6):1933-1938.

Workman, S.R. and R.W. Skaggs. 1990. PREFLO: A water management model capable of simulating preferential flow. Transactions of the ASAE 33(6):1939-1948.

Workman, S.R. and R.W. Skaggs. 1991. Evaluation of the water management model. PREFLO. Transactions of the ASAE 34(5):2053-2059.

Workman, S. R. 1999. Personal communication. Department of Biosystems and Agricultural Engineering, University of Kentucky, Lexington, Kentucky.

CHAPTER 7

USING WEPP-WTM MODEL FOR THE DARA WRSIS SITE WATERSHED

7.1 INTRODUCTION

Linked Wetland-Reservoir-SubIrrigation Systems (WRSIS) are being evaluated to understand how they can be constructed, operated and managed to improve the quality of water that enters surface water bodies from cropland, help achieve consistently high crop yields, and increase wetland acreage (Hothem, 1999). In this system, a wetland is constructed to receive runoff and subsurface drainage water from adjacent cropland area during periods of high rainfall. After preliminary sedimentation at the wetland, the collected water can be pumped into the constructed water supply reservoir or diverted out of the system. The wetland functions as a filter to detain sediments and chemicals. The reservoir serves as a supplemental water supply source for subirrigating corn and soybean crops in adjacent fields during dry periods. Three such systems have been developed in Northwest Ohio. The Defiance Agricultural Research Association (DARA) site in Defiance, Ohio is one of them.

Water Erosion Prediction Project-Water Table Management (WEPP-WTM) model has been developed to improve water balance, runoff, drain flow, and water table depth prediction capabilities of WEPP for cropland where water table management systems exist or are planned. The estimated runoff related sediment yield was predicted using the erosion prediction components of the WEPP hillslope model (Ascough II et al., 1997; Baffaut et al., 1997; Flanagan and Livingston, 1995; Flanagan and Nearing, 1995; Lane and Nearing, 1989; Liu et al., 1997; and Nearing et al., 1989). The model can be used as a design, evaluation, and/or management tool for WRSIS systems. For example the model can be used as a tool for managing water table depths and determining subirrigation flow rates (supplied from the reservoir) needed to raise midspace water table depths in subirrigated fields. It can be used to predict daily water table depth fluctuations at subirrigated, controlled drained, subsurface drained, and undrained fields. This model also can be used to predict runoff, sediment yield, drain flows, and subirrigation or controlled drainage excess flows.

The overall purpose of the research presented in this chapter was to apply the WEPP-WTM model for one of the WRSIS field sites. The specific objectives are: a) prepare input data to be used with the WEPP-WTM linked WEPP watershed model for predicting runoff volumes entering the wetland of the DARA WRSIS site; and b) compare runoff volumes predicted by the linked model with measured runoff volumes for a seven month time period in 1999.

7.2 MATERIALS AND METHODS

7.2.1 Linked WEPP-WTM and WEPP watershed model

The modification and initial evaluation of WEPP-WTM were presented in Chapters 5 and 6, respectively. The main modifications necessary to produce WEPP-WTM as discussed in Chapter 5 were made on the water balance algorithms of WEPP hillslope model. The WEPP watershed model was built as an extension of the WEPP hillslope model. The model was developed to predict erosion effects from agricultural management practices and to accommodate spatial and temporal variability in topography, soil properties, and land use conditions within small agricultural watershed (Flanagan and Livingston, 1995). The WEPP hillslope model outputs computes runoff volume, peak runoff rate, and sediment concentration and these values are stored in a hillslope-to-watershed pass file and then read in and used by the channel component of the WEPP watershed model. The modifications made in the WEPP hillslope model also partially covered the water balance algorithms in the channel component of WEPP watershed model because both the hillslope and channel components of the WEPP watershed model use the same hydrologic algorithms. WEPP-WTM was linked with the WEPP watershed model in the same way as is currently done with the WEPP hillslope and watershed models.

7.2.2 Description of DARA WRSIS watershed

The small, flat agricultural watershed for the DARA site is located in Defiance county, Northwest Ohio. The site is located between the Defiance County airport and State Route 15. The land slope is between 0.05 and 1%. The site comprises about 11 ha (27 ac) of comparison (undrained and drained with different drain spacings and depths) and subirrigation plots with grassed waterways between these plots, and a constructed wetland and reservoir. The site has two separate 1.1 ha (2.7 ac) subirrigated fields, one termed the east field and the other the west field. Each field contains areas with two different subsurface drain spacings of 2.4 and 4.8 m (8 and 16 ft). A detailed topographical survey of the site, and a topographic map, many cross sections through channels, and stage-area-volume relationships for the wetland and reservoir were developed using the software package Surfer. The topographic map and a plan view of the site is given in Figure 7.1. Table 7.1 summarizes the water table management practices with their system parameters at the DARA plots. Figures 7.2 and 7.3 show the drainage system layouts at the subirrigated and comparison plots, respectively. Figure 7.2 also shows site monitoring instrument locations. A detailed description of instrumentation and monitoring plans for the site are given by Oztekin et al. (1998) and Hothem (1999).

Plot #	Water Table Management Practice	Drain Spacing (m)	Drain Depth (cm)	Drain Pipe Diameter (cm)	Area (ha)
1	undrained	-	-	-	1.7
2	subsurface drained	3.0 and 6.1	66.0-81.3	5.1	1.6
3	subsurface drained	6.1 and 12.2	86.4-76.2	10.0	1.6
4	surface drained	-	-	-	1.6
5	surface and subsur. drained	12.2 and 6.1	66.0-81.3	10.0	1.7
6	subirrigation	2.4	81.3	10.0	0.4
7	subirigation	4.9	81.3	10.0	0.6
8	subirrigation	2.4	81.3	10.0	0.4
9	subirrigation	4.9	81.3	10.0	0.6
10	surface drained	-	-	-	0.2
11	surface and subsur. drained	6.1 and 12.2	81.3	10.0	0.2

Table 7.1. Water table management practices with system parameters on the plots of DARA WRSIS watershed.

After the survey it was determined that the catchment area for this subwatershed is about 12.8 ha (32 ac). The overland flow elements and predominate runoff directions are given in Figure 7.4. The runoff catchment area includes some parts of plots 3, 4, 5, 8, 9, the runway, taxiway, grassed waterways between the plots, and complete subirrigated plots of 6 and 7. The main portion of runoff coming from the comparison plots, half of taxiway and runway, and the grassed waterways between the plots enters the wetland on its northwest edge. The runoff at this

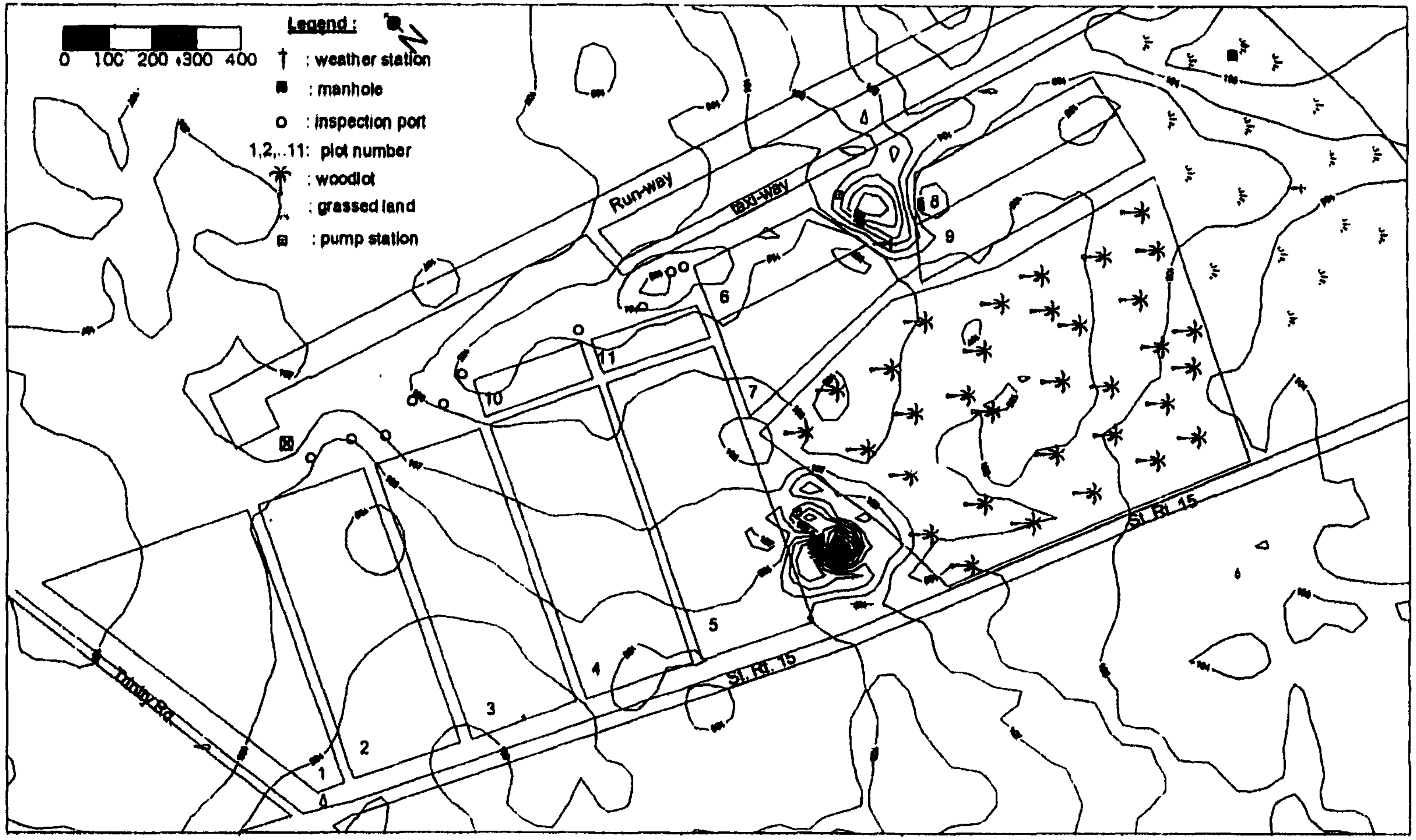

Figure 7.1. A plan of view of the Defiance Agricultural Research Association (DARA) WRSIS site in Defiance County, Ohio

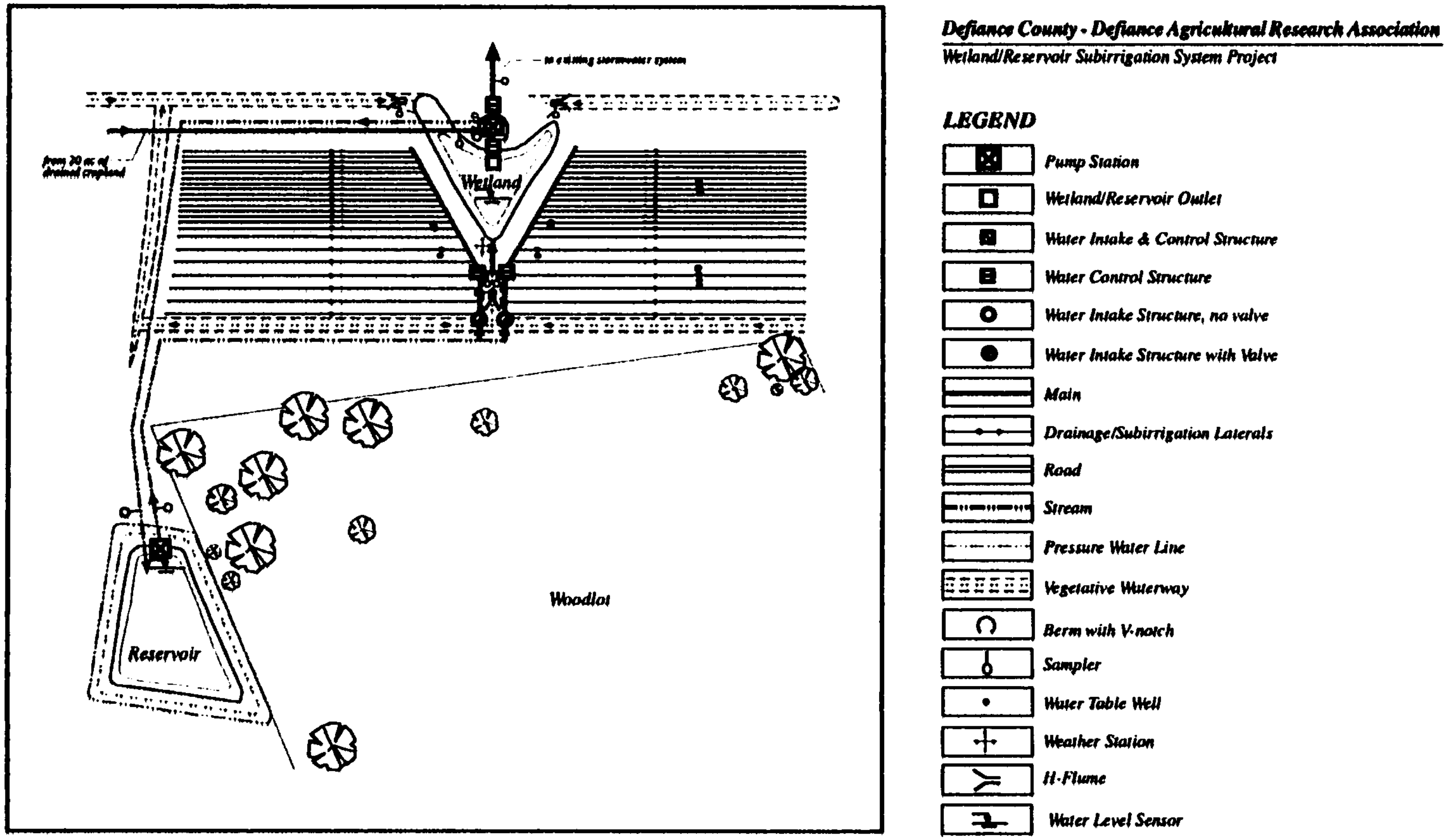

Figure 7.2 DARA WRSIS monitoring locations

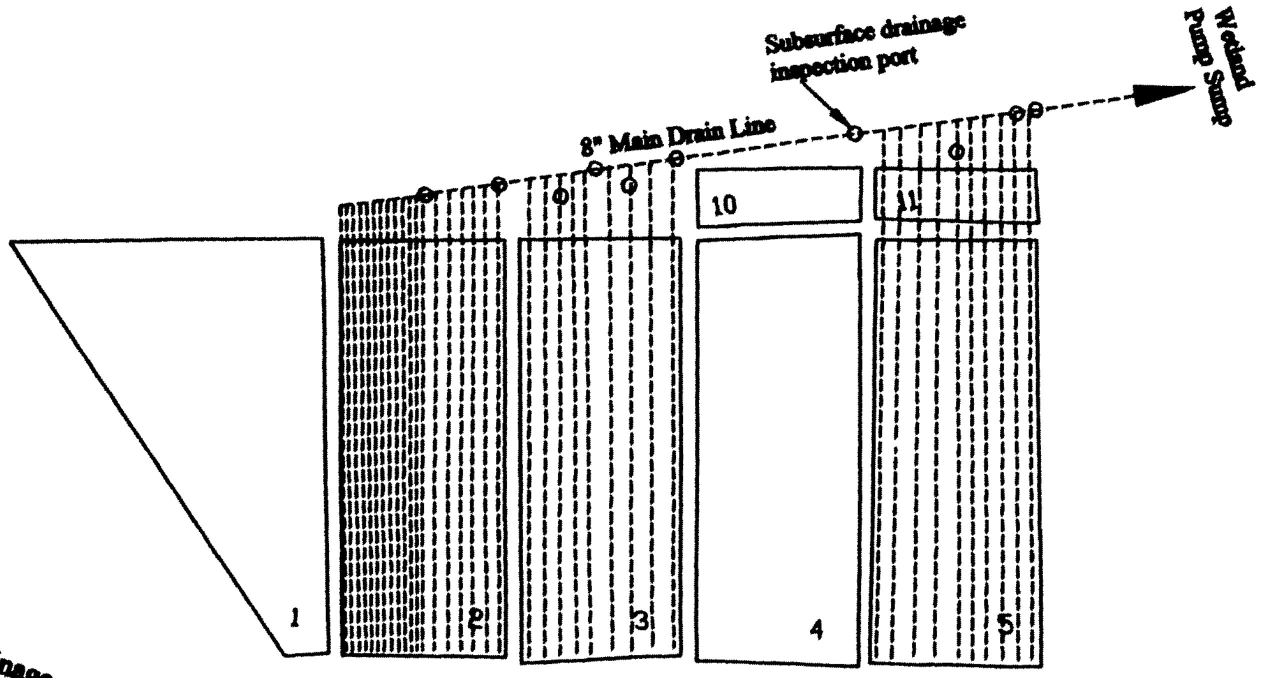

Figure 7.3. Drainage system layout of the DARA WRSIS comparison plots (the numbers relate to the plot descriptions in Table 7.1)

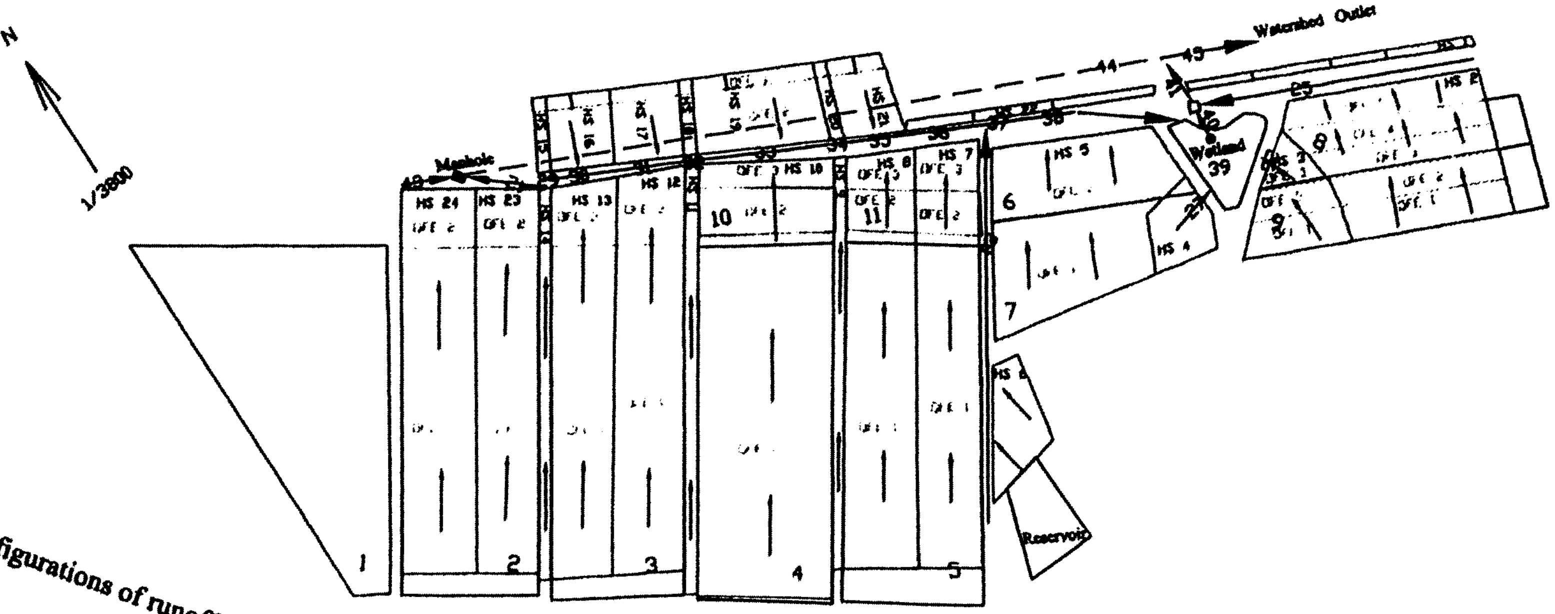

Figure 7.4. The configurations of runoff directions, hillslopes (HS), overland flow elements (OFE), and channels in DARA WRSIS watershed

location is measured using a 0.61-m (2-ft) H flume with a stilling well and strip chart recorder. A plan view of the flume is given in Figure 7.5. Most of the runoff from plot 2 goes to the manhole located between this plot and the runway. Runoff from plot 1 goes to the ditch located on the west of this plot. Runoff from small portions of the east and west subirrigation fields directly enter the wetland without passing through any runoff measurement instrument. Runoff from the rest of the west subirirgation field also enters the wetland through 0.61-m H flume. Finally, runoff from the rest of the east subirrigation plots (8, 9) is routed directly into the pump sump located between the wetland and the taxiway.

7.2.3 System Description

A schematic view of the main water control structures with water transfer lines at the DARA site is given in Figure 7.6. The pump adjacent to the reservoir (pump station A) is used to pump water from the reservoir to the subirrigation fields. Water is added to the subirrigated fields at the water intake structures. Excess subirrigation and drainage water from the subirrigation plots are routed through subsurface drains to the wetland. Water table levels in these fields are controlled by in-line control structures. All subsurface drainage flows from the comparison plot area are transferred to the pump sump at station B by a 20 cm (8 in) diameter corrugated plastic pipe. Not shown on Figure 7.6 is the wetland inlet where surface flows from the comparison plot area and other parts of the watershed enter the wetland through a flume. Also, there are other small areas producing surface flow and these flows enter pump station B directly. Outflow from the wetland is controlled by in-line control structure. Wetland outflow goes to the pump sump (pump station B) by gravity. There are two pumps in pump station B, which are used to transfer water collected from the wetland to the reservoir. Water from the pump sump can be allowed to leave the site if desired, using another in-line control structure located between the pump sump and the watershed outlet. In addition, this in-line control structure is used as the watershed outlet control structure.

7.2.4 Model Input Data

The watershed was divided into 24 HillSlope elements numbered on Figure 7.4 as HS1-HS24 and 20 channel elements numbered on Figure 7.4 as 25-45 with uniform soil, management (different water table management system parameters), and general overland flow direction. Based on the different crops, water table management practices, and drainage system parameters, the hillslopes were further divided into Overland Flow Elements (OFE). The linked model also

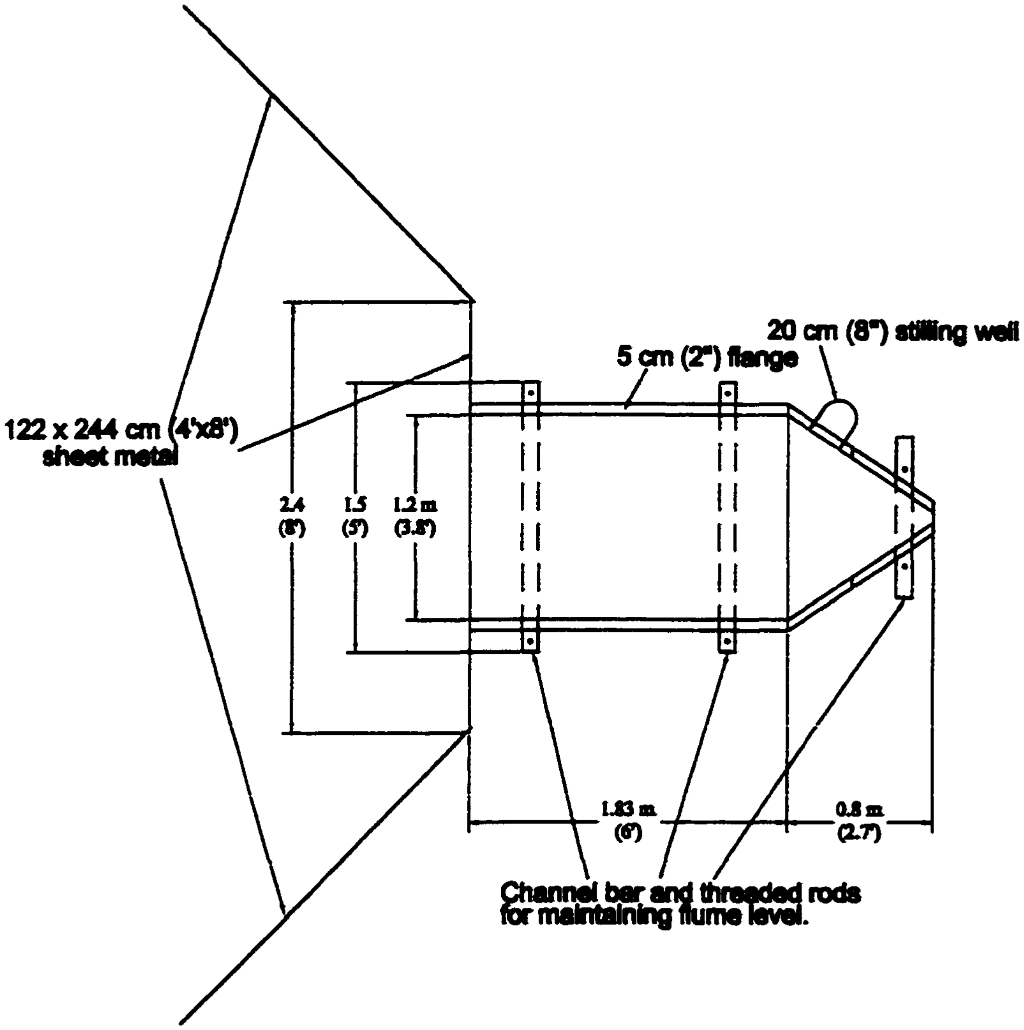

Figure 7.5. Overhead view of the 0.61-m (2-ft) H flume used at the DARA-WRSIS site.

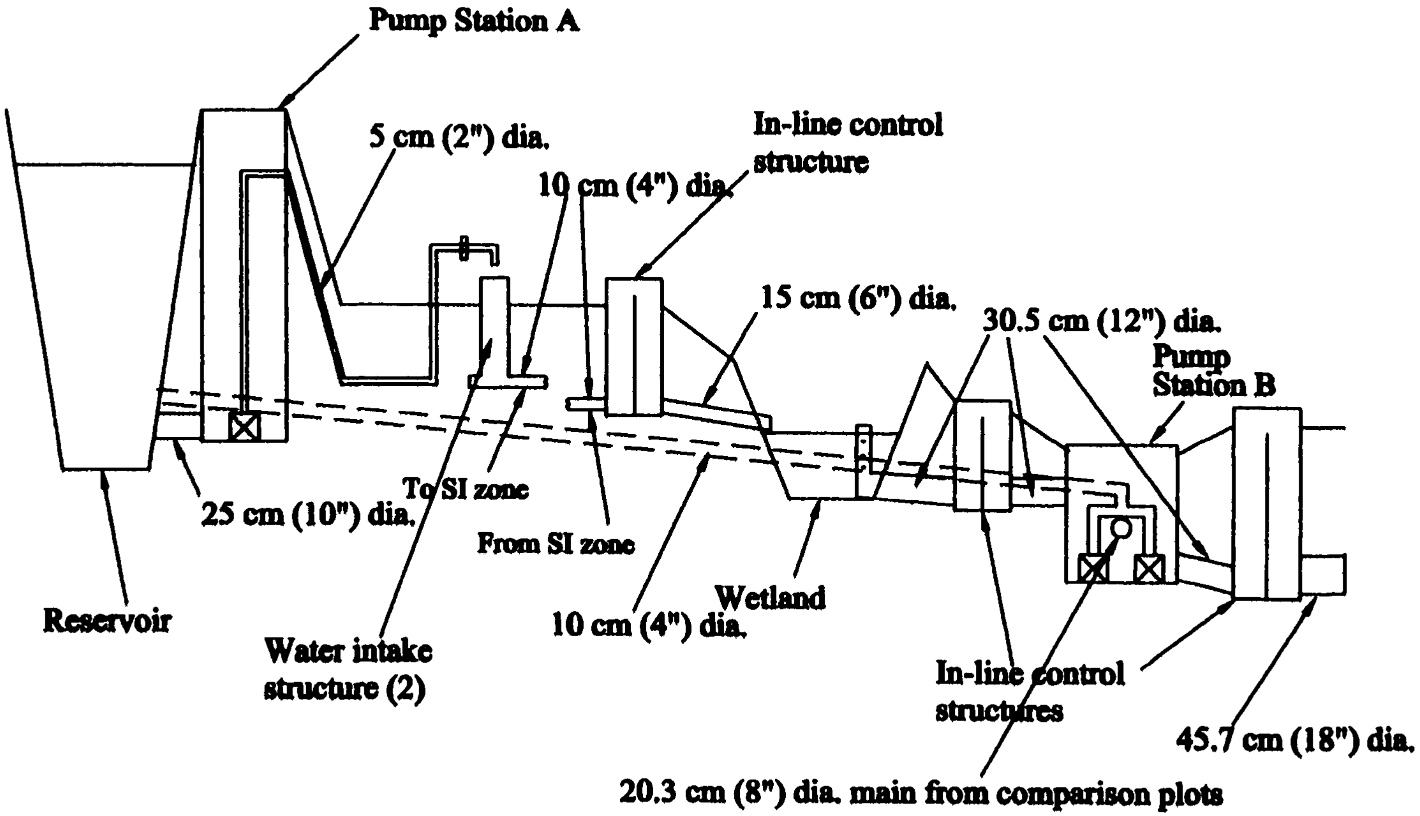

Figure 7.6. A schematic structures and water transfer lines (reservoir, wetland, and subirrigation field) (vertically to scale) at the DARA-WRSIS site.

requires information about weather, soils, management, topography, channel geometry and outlet structure, and impoundment parameters.

7.2.4.1 Weather input data

At the beginning of 1999, a portable Campbell Scientific weather station with CR10X data logger was setup at the site. Wind speed and direction, solar radiation, air minimum and maximum temperatures, relative humidity, evaporation, and precipitation are measured every two minutes, and recorded hourly and daily. Data from this weather station were used in this analysis. Rainfall inputs were prepared in an hourly breakpoint format. Solar radiation (mmol/m^2) was measured using both quantum and pyranometer sensors. Since the pyranometer sensor measures total radiation (global sun plus sky radiation), the data obtained from this sensor were converted from mmol/m^2 to Langleys/day, which is the unit used in WEPP (mmol/m^2 x 2062.05 = Langleys/day).

The model also needs daily dew point temperatures. Since daily dew point temperatures were not measured at the site, they were calculated using two different methods. In the first method, the equations given in the ASHRAE Handbook (1993) were used. For the temperature range of 32 to 200 °F, the equation used is:

$$t_d = 100.45 + 33.193\alpha + 2.319\alpha^2 + 0.17074\alpha^3 + 1.2063(P_w)^{0.1984} \text{........................} 7.1$$

For the temperatures below 32 °F, the equation is:

$$t_d = 90.12 + 26.412\alpha + 0.8927\alpha^2 \text{...} 7.2$$

where: t_d is the dew point temperature (°F); P_w is the water vapor partial pressure (psia); and α is the natural logarithm of the water vapor partial pressure. The water vapor partial pressures (P_w) for temperatures below 32 °F were calculated using the following equations:

$$\ln(P_w) = C_1/T + C_2 + C_3T + C_4T^2 + C_5T^3 + C_6T^4 + C_7\ln(T) \text{......................} 7.3$$

and for temperature range of 32 °F to 392 °F, the water vapor partial pressure was calculated using the following equation:

$$\ln(P_w) = C_8/T + C_9 + C_{10}T + C_{11}T^2 + C_{12}T^3 + C_{13}\ln(T) \text{..............................} 7.4$$

where: T is absolute average daily temperature (°R= °F+459.67); C_1=-1.0214165E+4; C_2=-4.8932428; C_3=-5.3765794E-3; C_4=1.9202377E-7; C_5=3.5575832E-10; C_6=-9.0344688E-14; and C_7=4.1635019; C_8=-1.0440397E+4; C_9=-1.1294650E+01; C_{10}=-2.7022355E-2; C_{11}=1.2890360E-5; C_{12}=-2.4780681E-9; and C_{13}=6.5459673.

The second method that was used to calculate dew point temperatures, the equation given by James (1993) was used as:

$$T_d = \frac{429.4 - 237.3\ln(e_a)}{\ln(e_a) - 19.08} \dotfill 7.5$$

where: T_d is dew point temperature (°C) and e_a is the vapor pressure of air (mbar). The parameter e_a is calculated using the following equation:

$$e_a = e_{sa}(RH/100) \dotfill 7.6$$

where: RH is the relative humidity (%), and e_{sa} is the saturation vapor pressure at air temperature T_a (°C). The parameter e_{sa} is calculated as:

$$e_{sa} = \exp\left(\frac{19.08T_a + 429.4}{T_a + 237.3}\right) \dotfill 7.7$$

Both methods give the same results for daily dew point temperatures for the seven month simulation period in 1999.

Weather data for 1996, 1997, and 1998 were obtained from the Midwestern Climate Center[1] measured at Toledo, Ohio, 75 km (46.5 mi) north-northeast from the site.

7.2.4.2 Slope data

The topographic and cross section information described earlier were used to estimate slope steepness values for the hillslopes and channels.

7.2.4.3 Plant/Management data

The major crops grown on the comparison plots for the years 1996 through 1999 were soybean, corn, soybean, and winter wheat, respectively. Corn and soybean were grown on the

---

[1] : Illinois State Water Survey, 2204 Griffith Drive, Champaign, IL 61820-7495.

subirrigation plots. The crops, planting and harvesting dates, for the comparison plots, and similar information for the subirrigated plots along with subirrigation start and ending dates for the last four years are given in Table 7.2. All crops in all years were no till. Soybean and corn were planted in 19 (7.5 in) and 76 cm (30 in) row widths, respectively. Soybean were planted with a no-till drill.

Subirrigation Plots:

Year	Crop	Planting Date	Harvesting Date	Subirrigation Start and Ending Dates
1996	Soybean(E&W)#	April 24*	September 15*	June 15*-August 20*
1997	Corn (E&W)	April 24	December 10	June 15-August 20*
1998	Corn (E)	May 18	November 2	June 15-August 20*
	Soybean (E)	May 20	September 30	June 15-August 20*
	Plowed/Fallow (W)		-	-
1999	Soybean (E)	May 17,June 21+	October 13	May 14-August 19
	Corn (W)	May 7	Not harvested yet	May 14-August 19

Comparison Plots:

Year	Crop	Planting Date	Harvesting Date
1996	Soybean	April 24*	September 15*
1997	Corn	April 24	December 10
1998	Soybean	May 20	September 30
	W. Wheat	October 9	-
1999	W. Wheat	-	July 8

*: Approximate date (assumed)
+: Replant
#: E : East field
W: West field

Table 7.2. Crops grown on the subirrigation and comparison plots at the DARA WRSIS watershed; planting and harvesting dates along with subirrigation start and ending dates.

As it can be seen from the topographic map (Fig. 7.1), there are grassed waterways between the plots, and there are also grasslands between the plots and taxiway. In 1999, these areas were mowed on June 8th, and the hay removed. For the other years of simulation, mowing date was not recorded, so, the same mowing date was used. The channels at the site were also covered by grass and they were simulated as grasslands, too. The taxiway and runway were simulated as pavement as suggested by Dr. John M. Laflen (1999).

The other plant specific parameters were obtained from tables given by Flanagan and Livingston (1995). These are default parameters for these plants. Percent residue cover for each crop was estimated from selected field photographs.

Drain spacings, depths, and pipe diameters for the subsurface drained and subirrigated plot areas were given in Table 7.1. Drainage coefficients for the water table management systems at the DARA plots were calculated using the equation given in the DRAINMOD User Manual (Workman et al., 1986):

$$DC = 8640000 R^{2/3} S^{1/2} A_t /(A_d n) \quad \text{.......} 7.8$$

where: DC is the drainage coefficient (cm/day); R is the hydraulic radius (m); S is the slope of the drain pipe; A_t is the cross sectional area of drain pipe (m^2); A_d is the area drained by pipe (m^2); and n is the roughness coefficient of the drain pipe. The effective radius of these drain pipes were obtained from the DRAINMOD User Manual. Since most of the plots at the site were surface drained, the runoff was assumed to move easily to the ground surface over the drain pipes. For this reason, a constant Kirkham depth value of 0.2 cm (0.08 in) was used for all plots except for the undrained plots. A 85 cm (33.5 in) initial water table depth at the beginning of each year was assumed for all plots. For the plots that were not subsurface drained, a 100 m (328 ft) drain spacing and a 5 cm (2 in) drain depth value with a very small drainage coefficient such as 1×10^{-5} cm/day (4×10^{-6} in/day) were used to simulate the soil profile water balance in these plots. These drainage system values were also used for channels, taxiway, and runway. During the subirrigation periods, weir depths were set to 25 cm (10 in) as recommended in the guidelines for managing the water table in subirrigated plots by Dr. R. L. Cooper and Dr. N. R. Fausey, as noted in the Maumee Valley Resource Conservation & Development Area Quality Assurance Plan (Czartoski et al., 1997). In the subirrigated plots, a 2 cm (0.8 in) ditch bottom depth with a 0.1 cm/cm (0.1 in/in) ditch side slope were used as the ditch parameters (10 cm; 4 in) diameter corrugated plastic). These values were recommended by Dr. Stephen R. Workman (1999) for subirrigated fields in which the water table is controlled by in-line control structures.

7.2.4.4 Soil data

From the Soil Survey of Defiance County (USDA, 1984), the dominant soils at the site are Paulding clay (Pa) and Roselms silty clay (RsA). The soil map from this survey report is illustrated in Figure 7.7. The soil profile descriptions for these soils are given in Appendix U. The Paulding and Roselms have four and five major layers, respectively. Using a Gidding's apparatus in 1988, soil samples from nine locations at the site were taken using standard 7.6 cm (3 in) diameter soil cores. Four soil samples (one from each layer) from each field location (shown in Figure 7.7) were obtained. Because of the depth limit of the apparatus, we could not get soil samples from some of the bottom layers. These samples were used to determine percent sand, clay, and organic matter, dry bulk density, cation exchange capacity (CEC), vertical and horizontal saturated hydraulic conductivity, and soil water retention data, as shown in Tables 7.3 and 7.4.

To determine the organic matter content, total carbon amounts were determined using the procedures given by Post (1956) and Soil Survey Staff (1972), and later these carbon amounts were multiplied by 1.724 (van Bemmelon factor). Dry bulk densities were obtained after dividing the weights of oven dry soil samples by core volumes. To determine the CEC values, pH values were determined (Soil Survey Staff, 1972), $BaCl_2$ –triethanolamine-extractable acidity of the samples were measured (Peech et al., 1947), and extractable Ca, Mg, K, and Na amounts were determined following the procedures given by Holmgren et al. (1977). Extractable acidity plus extractable Ca, Mg, K, and Na gave the total CEC values of each soil sample. To determine the vertical saturated hydraulic conductivity values of the soil samples, a constant head saturated hydraulic conductivity test was applied as described in Soil Physics 671 class notes (Lal, 1997). After running the constant head permeameter test for a long time period (some test took more than 24 hours), no water seepage was obtained for most of the soil samples.

In 1995, the horizontal saturated hydraulic conductivity values were determined in the field by Dr. Belcher from Michigan State University using a velocity permeameter. Dr. Belcher's unpublished findings stated that the horizontal saturated hydraulic conductivity values for DARA site ranged from 0.025 to 0.076 cm/hr (0.01 to 0.03 in/hour), with 0.051 cm/hr (0.02 in/hr) as the prevailing value. These determined horizontal saturated hydraulic conductivity values by Dr. Belcher were used instead of the vertical saturated hydraulic conductivity values. In the linked model, values of 0.076, 0.051, 0.025, and 0.025 cm/hr were used for the horizontal saturated hydraulic conductivity values for the first, second, third, and fourth layers of the soil profile, respectively.

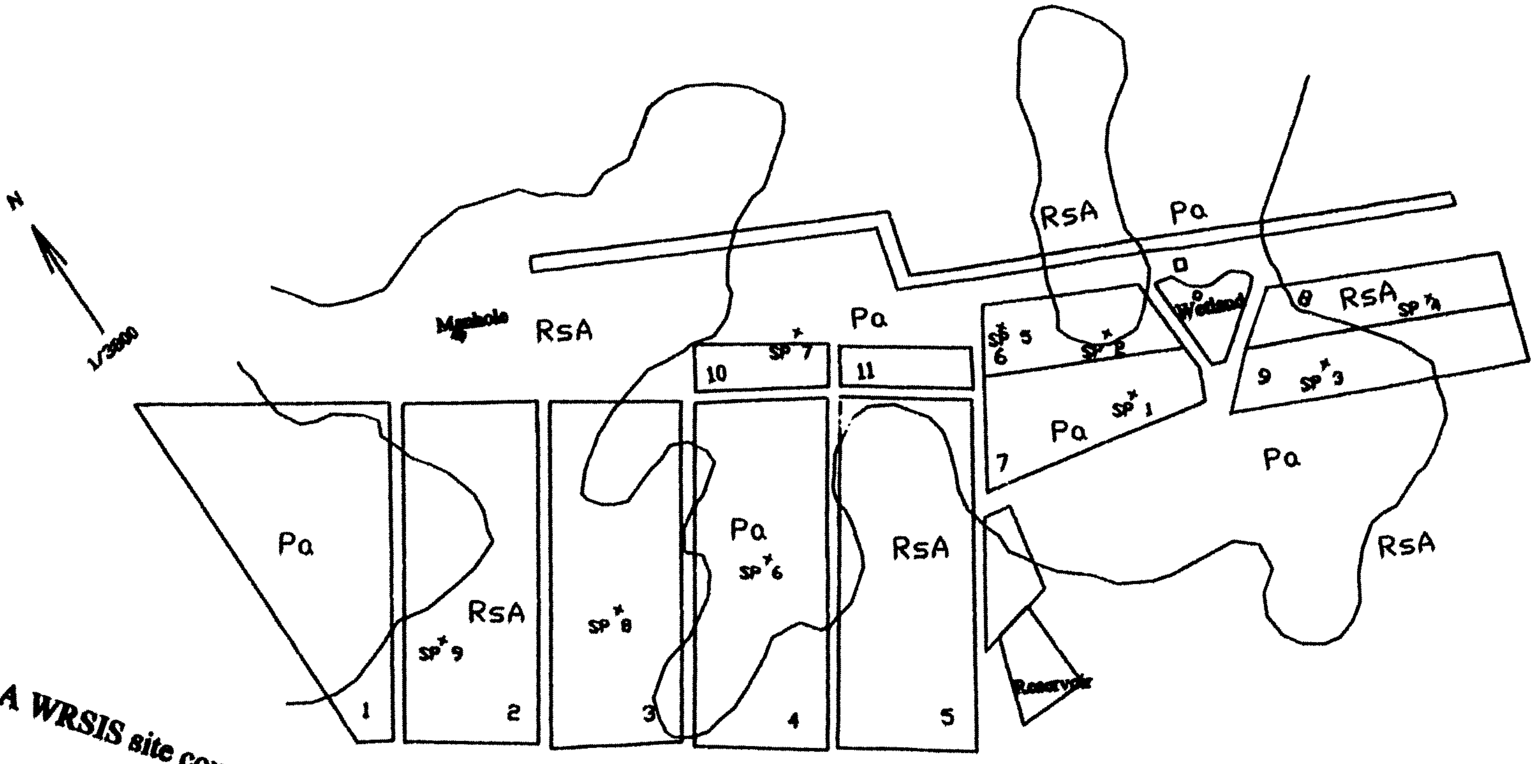

Figure 7.7. DARA WRSIS site county soil clasification boundaries with soil sample locations

Profile Number	Depth from Surface (cm)	Organic Matter (%)	Dry Bulk Density (g/cm^3)	Cation Exchange Capacity (meq/100 g soil)	pH	Vertical Sat. Hyd. Cond. (cm/hr)	Clay (%)	Sand (%)	Silt (%)
1	14	3.38	1.46	34.28	5.5	1.03	36.82	12.55	50.63
	32	2.60	1.34	31.67	5.4	1.15	40.64	8.70	50.66
	75	1.72	1.40	33.51	5.3	0.02*	44.11	4.05	51.84
2	20	2.27	1.50	27.18	5.6	8.88	48.26	18.20	33.54
	40	0.90	1.67	27.64	5.7	0.04	48.03	25.95	26.02
	75	0.88	1.62	36.45	7.4	0.18	42.00	12.85	45.15
3	20	5.96	1.11	38.01	4.7	0.08*	16.56	26.55	56.89
	35	2.26	1.45	35.12	4.5	0.05*	41.10	8.97	49.93
	55	1.46	1.41	41.28	5.1	0.01	42.26	4.50	53.24
	77	1.46	1.58	58.12	7.5	0.01$^+$	47.97	3.55	48.48
4	22	3.76	1.33	34.05	5.1	0.08*	27.98	17.75	54.24
	35	1.33	1.51	44.65	4.6	0.05*	47.97	3.60	48.43
	50	1.10	1.42	43.76	6.1	0.01	62.25	4.75	33.00
	60	1.24	1.54	51.66	7.6	0.01$^+$	53.69	1.70	44.61
5	20	3.02	1.44	43.28	7.1	0.08*	27.82	9.00	63.18
	35	2.76	1.46	33.01	5.9	0.01	43.26	4.93	51.81
	50	1.93	1.49	32.87	5.7	0.01	51.18	3.89	44.93
	81	1.88	1.43	32.90	5.8	0.01	39.41	6.10	54.49

Table 7.3. Organic matter, cation exchange capacity, pH, core method based vertical saturated hydraulic conductivity values with clay, silt, and sand percentages of DARA WRSIS site soils (soil samples taken late September and early October 1998).

(Table 7.3. continued)

6	21	2.22	1.50	30.75	6.6	0.08*	30.84	13.50	55.66
	36	1.15	1.55	28.50	4.5	0.04	42.93	7.96	49.91
	53	0.88	1.48	36.45	6.4	0.02*	62.25	4.50	33.25
	64	0.96	1.51	45.59	7.7	0.01	59.40	3.70	36.90
7	17	3.76	1.40	33.76	6.4	0.08*	25.13	19.10	55.77
	34	1.84	1.47	30.54	5.0	0.05*	42.12	11.87	46.01
	45	1.59	1.33	31.99	5.5	0.02*	53.69	10.40	35.91
	63	1.26	1.46	30.49	5.5	0.02*	39.41	12.55	48.04
8	18	2.45	1.44	31.89	6.1	0.03	39.41	13.05	47.54
	36	2.34	1.51	31.44	5.9	0.02*	30.84	12.75	56.41
	53	1.53	1.44	34.14	5.0	0.02*	47.97	5.30	46.73
	73	1.07	1.54	35.09	5.3	0.02*	51.68	6.80	41.52
9	21	2.50	1.51	30.94	6.0	0.08*	30.84	18.35	50.81
	34	1.22	1.52	39.26	4.5	0.04	45.12	5.30	49.58
	55	0.98	1.55	41.89	6.4	0.02*	68.11	4.85	27.04
	69	1.17	1.59	48.30	7.6	0.02*	59.40	4.25	36.35

*: horizontal saturated hydraulic conductivity measured by Dr. Belcher

+: previous layer's value

Profile Number	Depth (cm)	Suction (cm of water)					
		0	20	60	330	1000	15000
1	14	0.510	0.497	0.483	0.475	0.472	0.375
	32	0.514	0.498	0.485	0.469	0.466	0.345
	75	0.518	0.506	0.500	0.473	0.470	0.390
2	20	0.493	0.471	0.459	0.455	0.453	0.281
	40	0.411	0.401	0.395	0.379	0.371	0.295
	75	0.455	0.446	0.439	0.419	0.409	0.333
3	20	0.508	0.497	0.490	0.485	0.480	0.262
	35	0.482	0.478	0.475	0.456	0.450	0.329
	55	0.557	0.549	0.540	0.520	0.514	0.321
	77	0.484	0.481	0.479	0.477	0.470	0.348
4	22	0.480	0.473	0.470	0.469	0.461	0.287
	35	0.521	0.520	0.518	0.515	0.513	0.371
	50	0.616	0.614	0.613	0.610	0.604	0.364
	60	0.532	0.531	0.529	0.523	0.506	0.327
5	20	0.498	0.496	0.493	0.487	0.469	0.334
	35	0.499	0.498	0.497	0.469	0.457	0.328
	50	0.494	0.491	0.490	0.487	0.458	0.354
	81	0.483	0.481	0.479	0.455	0.448	0.353
6	21	0.447	0.443	0.441	0.440	0.434	0.313
	36	0.475	0.473	0.471	0.469	0.460	0.289
	53	0.553	0.546	0.544	0.543	0.513	0.354
	64	0.562	0.555	0.549	0.531	0.518	0.316
7	17	0.483	0.470	0.464	0.461	0.451	0.327
	34	0.557	0.549	0.543	0.536	0.478	0.310
	45	0.591	0.574	0.565	0.554	0.548	0.300
	63	0.565	0.559	0.555	0.547	0.501	0.335
8	18	0.484	0.479	0.476	0.474	0.461	0.335
	36	0.469	0.466	0.465	0.461	0.441	0.328
	53	0.579	0.577	0.573	0.570	0.567	0.365
	73	0.540	0.537	0.535	0.531	0.489	0.376
9	21	0.447	0.438	0.434	0.423	0.415	0.317
	34	0.510	0.509	0.507	0.502	0.479	0.341
	55	0.535	0.533	0.531	0.528	0.483	0.372
	69	0.486	0.483	0.481	0.478	0.434	0.337

Table 7.4. Soil moisture release characteristics of DARA-WRSIS site soils

Soil particle sizes (Table 7.3) were determined using the pipet method following the procedures described by Kilmer and Alexander (1949). Soil water characteristics (Table 7.4) were determined using a tension table and pressure plates following the procedures given in Soil Physics 671 class notes (Lal, 1997). For the taxiway and runway, a one layer soil with a thickness of 50 cm (20 in) and 99% clay percentage was used. Bulk densities just after tillage were estimated by increasing the calculated dry bulk density values (Table 7.3) by 10% (assumed). Three baseline soil erodibility parameters (interrill, rill, and critical shear stress) and the Green and Ampt effective hydraulic infiltration values of the soils were estimated using the WEPP default estimation equations given by Flanagan and Livingston (1995). The erodibility values for the pavement as suggested by Dr. Laflen (1999) were 10000 kgs/m^4, 0.00001 s/m, and 30 mm/h (2554272 lbs/ft^4, 0.00003 s/ft, and 1.18 in/h), respectively. For both of the soil types, a 152 cm (60 in) profile depth was used in the simulations.

7.2.4.5 Channel input data

The channel slopes and lengths were obtained from the topographic map and cross sections. In the field, channels 34, 35, 38, and 39 (Fig. 7.4) are buried corrugated plastic pipe, therefore an assumption was made that no erosion activity would occur in these channels. At first, these channels were simulated as pavement, which caused error in the model. Therefore, these channels were also simulated as natural channel; with a bed slope set equal to their friction slopes.

For other channels, the option of using CREAMS calculation method within WEPP given by the linked model was chosen. To calculate the peak runoff, the method from the EPIC model with WEPP was chosen, which is the preferred option by Flanagan and Livingston (1995) for small watersheds. The same erodibility values used for the hillslopes were also used for the channels depending on the closest soil sample location for each channel reach. Manning roughness coefficients for the channels were obtained from Schwab et al. (1993) and Flanagan and Livingston (1995). A constant depressional storage depth was used for each channel. These values were estimated using visual observation.

The linked model needs the flow conditions that exist at the outlet of a channel in order to calculate the energy gradeline when backwater effects are to be taken into account to calculate erosion on the channels (Flanagan and Livingston, 1995). The 0.61-m (2-ft) H flume cross section was simulated as the control section at the outlet of channel 32 (Fig. 7.4). The rating curve of the flume was obtained using the stage-discharge data for the 0.61 m H flume given by Grant and Dawson (1997) using the Microsoft Excel program. The resulting rating curve and stage-discharge data are given in Figure 7.8. The rating equation given in this figure was used to estimate field runoff rates through the 0.61-m H flume using the stage recorder data. In 1999, the maximum stage recorded was less than 20 cm.

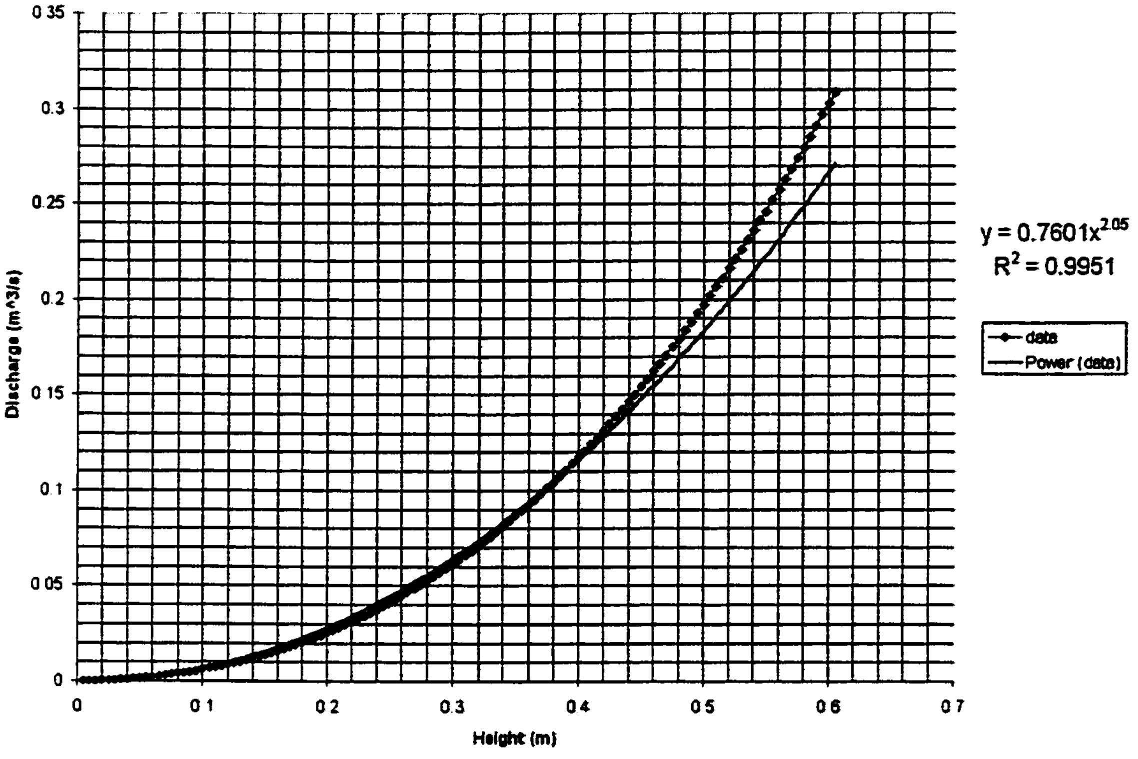

Figure. 7.8. The head-discharge relationships of the 0.61 m (2-ft) H flume used at the DARA-WRSIS site.

7.2.4.6 Impoundment data

In the linked model, the constructed wetland was simulated as an impoundment. The topographic map of the wetland is given in Figure 7.9, and data from this figure was used to develop the stage-area relationship illustrated in Figure 7.10. The stage-length-area data are given in Appendix V. A representative cross section view of the wetland with the outlet control structure is given in Figure 7.11. The stage at the lowest point of the wetland was assumed as zero. As mentioned before, flow from the wetland is mainly controlled by a 30 cm (12 in) in-line control structure, with a flash board width of 40.6 cm (16 in). There is a plan to cut a 5 cm (2 in)

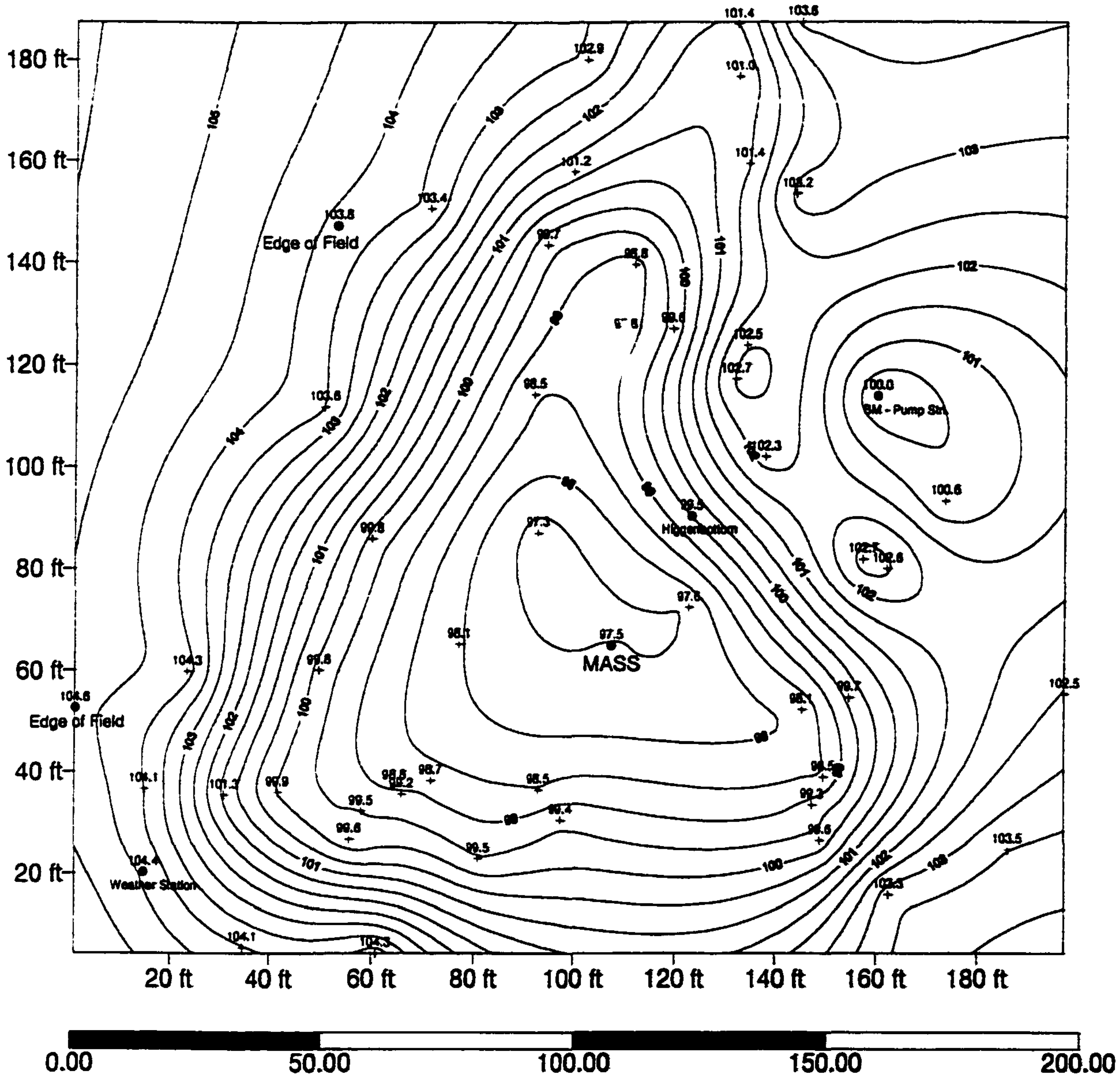

Figure 7.9. Defiance Agricultural Research Association (DARA) WRSIS wetland map (surveyed 5/23/99)

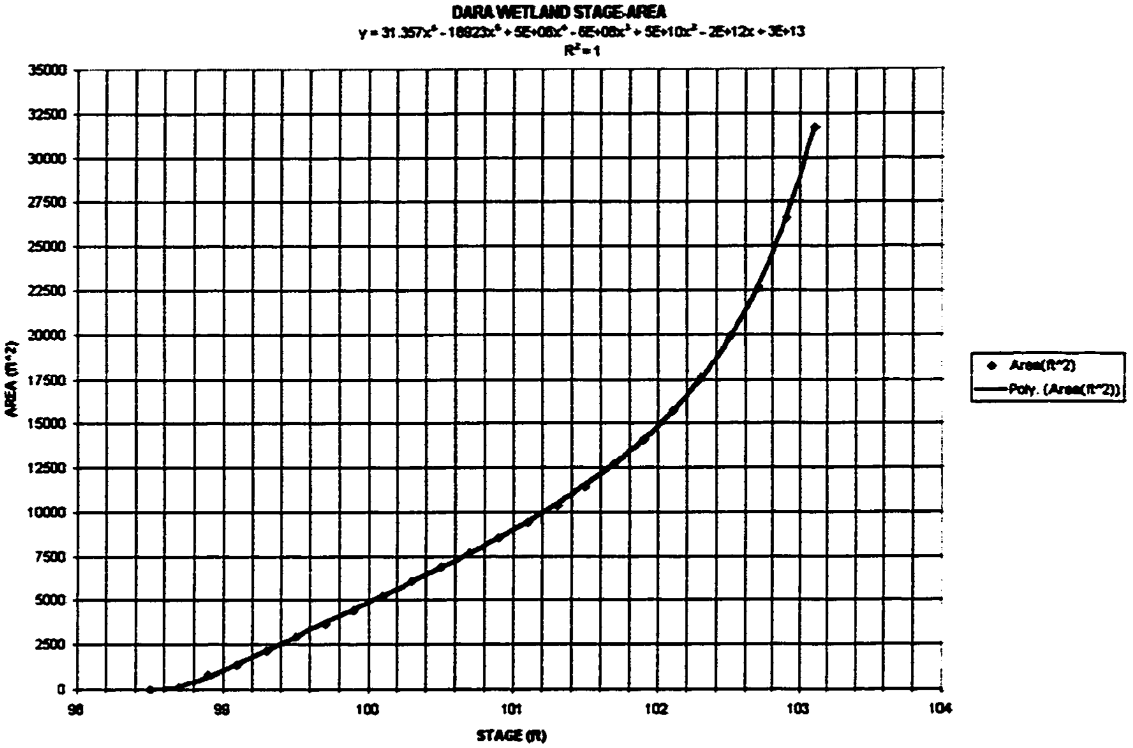

Figure 7. 10. The stage-area relations of the wetland at the DARA-WRSIS site.

diameter hole in one of the flashboards of the in-line control structure at the minimum stage allowable for drainage from the wetland based on the minimum inflow level for the higgenbottom riser. In the linked model, the in-line control structure and the hole were simulated as an emergency spillway with the user specified stage-discharge relationships. It is assumed that the bottom level of the hole is at the same level with the bottom of hickenbottom intake structure (Fig. 7.11). It is also assumed that the top flashboard in the inline control structure was set at an elevation of 1.10 m (3.6 ft). Flow from the hole was assumed orifice flow and estimated using an orifice flow equation given by Schwab et al. (1993):

$$Q = 5.218x10^{-3} h^{0.5} \qquad 7.9$$

where: Q is the discharge (m^3/s) and h is the head (m) from bottom of the hole. After assuming the flow over the top flashboard in the in-line control structure is free flowing rectangular weir flow, this flow was determined using the following equation (Grant and Dawson, 1997):

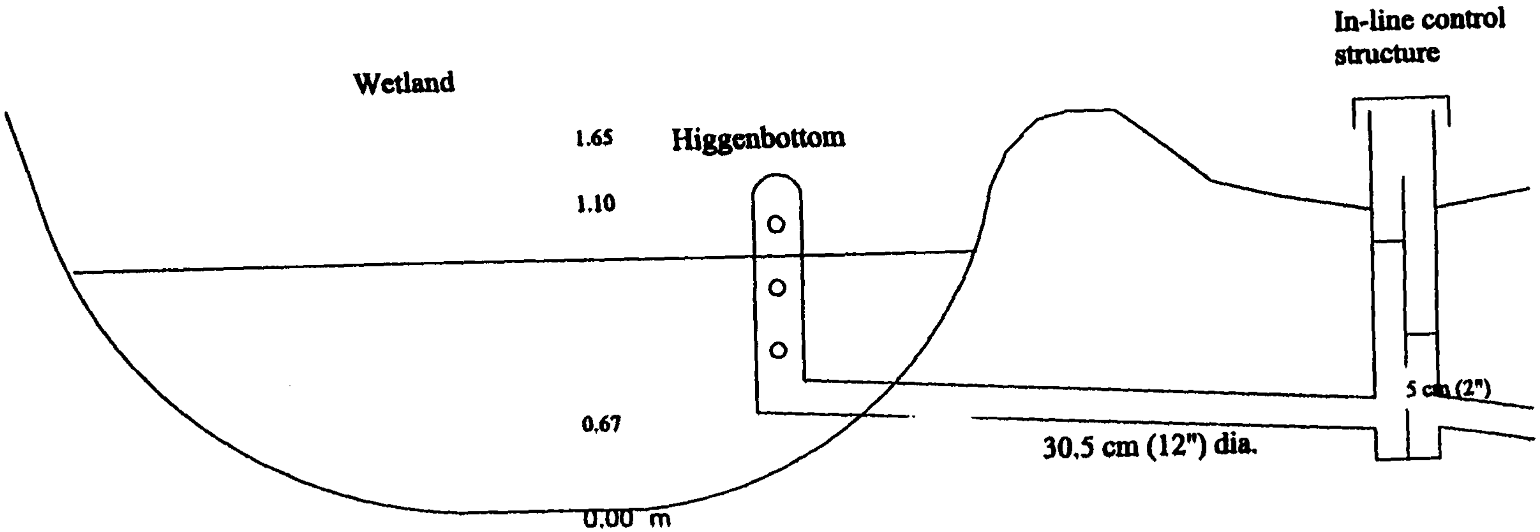

Figure 7.11. A representative cross section of the constructed wetland with its outlet control structure.

$$Q = 0.67356h^{1.5} \quad \text{.......... 7.10}$$

The stage-discharge relationship data for the hole and in-line control structure were obtained by determining the discharge rates from Equations 7.9 and 7.10 for 50 different head values. Figure 7.12 shows this relationship.

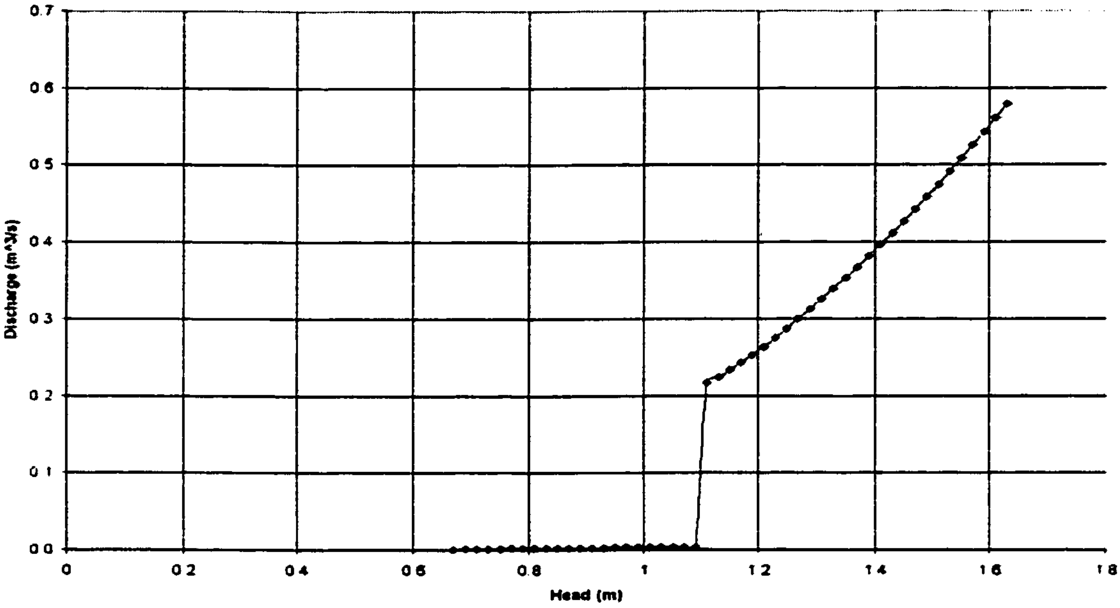

Figure 7.12. Head-discharge relations for the in-line control structure controlling water level in the wetland at the DARA WRSIS site.

7.2.4.7 The structure file

The watershed structure file describes the watershed configuration. For each channel element or impoundment, it indicates what hillslopes, channels and/or impoundments are draining into it from the top, or laterally from the left or right (Flanagan and Livingston, 1995). The watershed structure file was created using the locations of hillslopes and channels, and their relation to each other as given in Figure 7.4. This file is given in Appendix W.

7.3 RESULTS AND DISCUSSION

Runoff depth measurements from the 0.61-m (2-ft) H flume at the DARA WRSIS site started in February in 1999. During the measurement period, most of the runoff to the flume came from the comparison plots. The daily measured and WEPP-WTM linked WEPP watershed model predicted runoff volumes are given in Figure 7.13 for a seven month (February 11-August 20) period in 1999. During this time period, nine main runoff events were recorded. The measured rain depths for these events are given in Table 7.5. From the recorded runoff depth charts, it was noted that the float in the stilling well froze many times during February and March. Therefore, reliable runoff depth readings could not be obtained during these months. Starting in April, the linked model underpredicted runoff for several events. Then on days 112-113, 142-143, and 151, the model overpredicted runoff by 255, 300, and 150%, respectively. However, the timing of runoff predicted by the model matched the observed. The elevation difference between the bottom of the flume and the top of the emergency spillway outlet located between the flume and the taxiway is about 30 cm (12 in). The recorded runoff depths in the flume during these events did not go beyond 17 cm (7 in.), therefore all the runoff coming from the comparison plots going into the flume was measured.

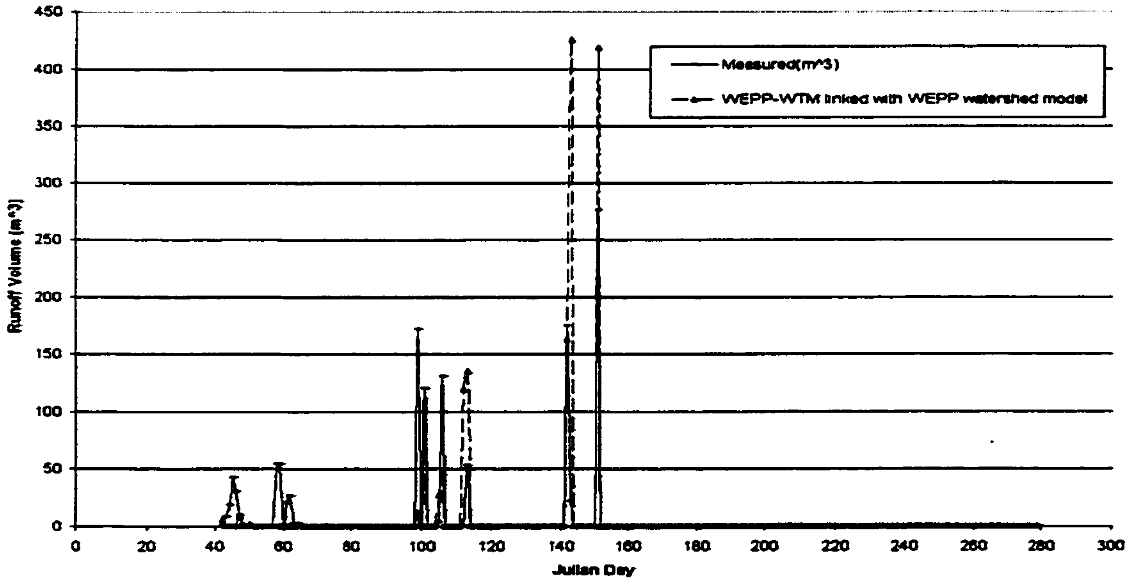

Figure 7.13. Daily measured and WEPP-WTM linked WEPP watershed model predicted runoff volumes passing through the 0.61-m (2-ft) H flume at the DARA-WRSIS site during February through May 1999.

Date	Julian Date	Measured Rainfall Depth (cm)
April 9, 1999	99	3.25
April 11, 1999	101	1.40
April 15, 1999	104	2.30
April 16, 1999	105	1.00
April 22, 1999	112	2.20
April 23, 1999	113	2.00
May 22, 1999	142	1.90
May 23, 1999	143	4.90
May 31, 1999	151	4.90

Table 7.5. The measured daily rainfall which caused mainly runoff events at the DARA WRSIS site during February through August of 1999.

7.4 SUMMARY

The overall purpose of the research presented in this chapter was to evaluate the WEPP-WTM model for one of the WRSIS field sites. The specific objectives were: a) prepare input data to be used with the WEPP-WTM linked WEPP watershed model for predicting runoff volumes entering the wetland of the DARA WRSIS site; and b) compare runoff volumes predicted by the linked model with measured runoff volumes for a seven month time period in 1999.

Most of the input data except horizontal saturated hydraulic conductivity values for the linked model were prepared.

A seven month period is a short time to evaluate a watershed model, especially when only two months of flow measurements are valid. In addition, the horizontal saturated hydraulic conductivity values obtained using the velocity permeameter were used in the model, and these values are considered low compared to visual observations of watertable depths and flows at the site. Therefore, further conductivity tests should performed and the model reevaluated. Lastly, because of the unavailable of field measured drain flows, subirrigation flows, water table depths, and sediment yields, these values could not be evaluated.

7.5 REFERENCES

Ascough II, J.C., C. Baffaut, M.A. Nearing and B.Y. Liu. 1997. The WEPP watershed model: I. Hydrology and erosion. Transactions of the ASAE 40(4):921-933.

ASHRAE Handbook. 1993. Fundamentals, I-P Edition. American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc. Atlanta, GA.

Baffaut, C., M.A. Nearing, J.C. Ascough II and B.Y. Liu. 1997. The WEPP watershed model: II. Sensitivity analysis and discretization on small watersheds. Transactions of the ASAE 40(4):935-943.

Czartoski, B.J., N. Fausey, L. C. Brown and R.L. Cooper. 1997. Maumee Valley Resource Conservation & Development Area Quality Assurance Plan, Defiance, Ohio.

Flanagan, D.C. and S.J. Livingston (Eds.). 1995. WEPP user summary. NSERL Report No. 11. USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, Indiana. 131 p.

Flanagan, D.C. and M.A. Nearing (Eds.). 1995. WEPP technical documentation. NSERL Report No. 10. USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, Indiana. 284 p.

Grant, D.M. and B.D. Dawson, 1997. Isco Open Channel Flow Measurement Handbook.Lincoln, NE. 501 p.

Holmgren, G.S., R.L. Juve, and R.C. Geschwender. 1977. Amechanically controlled variable-rate leaching device. Soil Science Society of America Journal. 41(6):1207-1208.

Hothem, J. H. 1999. Modeling of flow-routing in a linked wetland-reservoir-subirrigation system (WRSIS) using Simulink. Master of Science Thesis. Ohio State University. Columbus, Ohio. 263 p.

James, L.G. 1993. Principles of Farm Irrigation System Design. Krieger publishing company, Malabar, Florida. 543 p.

Kilmer, V.J. and L.T. Alexander. 1949. Methods of making mechanical analysis of soils. Soil Science 68(July-December):15-24.

Laflen, J. M. 1999. Personal communication. Agricultural Engineer, USDA-Agricultural Research Service. USDA Soil Tilth Center Ames, Iowa.

Lal, R. 1997. Soil Science 671. Soil Physics Practical Manual. Ohio State University. 78 p.

Lane, L.J. and M.A. Nearing (Eds.). 1989. USDA-Water erosion prediction project: Hillslope profile model documentation. NSERL Rep. No. 2, USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, Indiana. 265 p.

Liu, B.Y., M.A. Nearing, C. Baffaut and J.C. Ascough II. 1997. The WEPP watershed model: III. Comparisons to measured data from small watersheds. Transactions of the ASAE 40(4):945-952.

Nearing, M.A., D.I. Page, J.R. Simanton and L.J. Lane. 1989. Determining erodibility parameters from rangeland field data for a process-based erosion model. Transactions of the ASAE 32(3):919-924.

Oztekin, T., N.M. N'Jie, J. Hothem, L. Luckeydoo, L.C. Brown, N.R. Fausey, B.J. Czartoski, and G. Mills. 1998. Monitoring system for water quality and quantity, and ecological parameters at the DARA wetland-reservoir subirrigation system site. An ASAE Presentation Paper No. 98-2110.

Peech, M.L., A. Dean, and J.F. Reed. 1947. Methods of soil analysis for soil-fertility investigations. USDA Circular No. 757. U.S. Government Printing Office, Washington, D.C.

Post, G.J. 1956. A study of three methods for determination of organic carbon in Ohio soils of several great groups and the profile distribution of carbon-nitrogen ratios. M.S. Thesis, The Ohio State University.

Schwab, G.O., D. D. Fangmeier, W. J. Elliot, and R. K. Frevert. 1993. Soil and Water Conservation Engineering. John Wiley & Sons, Inc., New York. 507 p.

Soil Survey Staff. 1972. Soil Survey Laboratory Methods and Procedures for Collecting Soil Samples. Soil Survey Investigations Report No. 1. USDA Soil Conservation Service. U.S. Govt. Printing Office, Washington D.C.

USDA. 1984. Soil Survey of Defiance County, Ohio.United States Department of Agriculture-Soil Conservation Service. 246 p.

Workman, S.R., R.W. Skaggs, J.E. Parsons and J. Rice (Eds). 1986. DRAINMOD User's Manual. Biological and Agricultural Engineering Department, North Carolina State University, Raleigh, North Carolina. 90 p.

Workman, S. R. 1999. Personal communication. Department of Biosystems and Agricultural Engineering, University of Kentucky, Lexington, Kentucky.

CHAPTER 8

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Runoff and subsurface drainage waters can be harvested in soil and water conservation structures, like constructed wetlands, ponds, and reservoirs, and the harvested water can be used for irrigation and other purposes. In Northwest Ohio in the Ohio portion of the Maumee River basin, three constructed wetlands have been designed, constructed, and linked with water supply reservoirs for corn and soybean production using subirrigation. These systems are called Wetland-Reservoir-SubIrrigation Systems (WRSIS), and they consist of four separate components: a constructed wetland, a water supply reservoir or pond, a subirrigated field and a subsurface drainage comparison area. The overall purpose of the WRSIS project is to demonstrate how construction and management of wetlands coupled with subirrigation can be economically profitable for farmers, thus stimulating the adoption of wetlands and reducing adverse impacts of agricultural runoff in the Maumee River Basin (Brown et al., 1998).

To date, there has been no research completed on the impact of a WRSIS to provide flood control, reduce erosion, improve water quality, control nutrient cycles, and detain sediment, runoff and subsurface drainage water. In addition, there is no one computer simulation model that has the capability to simulate the components and functions of the WRSIS systems at the field or watershed scale. The Water Erosion Prediction Project (WEPP) hillslope and watershed models (Flanagan and Nearing, 1995) were of interest to the author and his goal to model the efficiency of runoff, subsurface drainage water, and sediment detainment capacity of the WRSIS. However, some model modifications, especially in the water balance algorithms of the WEPP hillslope model were needed. While the current version of the WEPP hillslope model (Flanagan and Nearing, 1995) is considered a robust erosion prediction model, it contains little more that a basic subsurface drainage component. In addition, the WEPP model does not have the capability to adequately model the hydrology of agricultural lands that have controlled drainage and subirrigation systems on them, and subsequently the impact of controlled drainage and subirrigation on soil loss.

The overall goal of this research was to modify the WEPP hillslope model, so that when it is linked with the WEPP watershed model, the linked model can be used to route runoff, subsurface drainage and subirrigation waters and sediment through the components of a WRSIS. The modified model is called Water Erosion Prediction Project-Water Table Management (WEPP-WTM). In addition, several drainage related studies were identified and completed.

This chapter contains a summary of the work presented in each of the preceding chapters, and the main conclusions and recommendations for future work. Below each chapter is presented individually along with their specific objectives

8.1 Chapter 2. Drainage Modeling Studies Leading to Improved Runoff and Drain Flow Prediction Capability

The results of a series of background studies thought to be of interest and necessary towards the improvement of the predictive capability of WEPP were presented in this chapter. Measured drain flow and runoff data from the drainage experiment at the OARDC North Central Branch station (Schwab et al., 1963; 1975; and 1985) were used in this study.

8.1.1 Objective 1: Hydraulic Conductivity Evaluations

The first objective was to evaluate runoff and drain flow predictions from DRAINMOD, using a range of saturated hydraulic conductivity data sets developed for the same site derived from seven different K_{sat} estimation methods. DRAINMOD (Version 4.6) simulations were conducted for the years 1962-1964, and 1967-1971. Model predictions were compared to measured outflows from Schwab et al. (1963; 1975; and 1985). The analyses showed that no one K_{sat} estimation method provided the smallest deviation in outflows when individual years were considered, except for drain flow in 1967-1971. For these years, the simulation results with the van Schilfgaarde equation estimated K_{sat} values produced the smallest average deviation. The van Schilfgaarde equation estimated K_{sat} simulations also produced the smallest deviation in runoff in three of the five years that also had the smallest drain flow deviations. Overall, the simulation results with the van Schilfgaarde equation estimated K_{sat} values produced the smallest total deviation for both drain flow and runoff over all eight test years. The rank order (smallest to largest total deviation) of the K_{sat} methods for drain flow were van Schilfgaarde, Hooghoudt, and Kirkham equations estimated K_{sat} methods, followed by auger hole, monolith, core methods, and then the MUUF soil database method. The rank order of the K_{sat} methods for runoff was van Schilfgaarde, Hooghoudt, Kirkham, auger hole, MUUF soil database, core, and Monolith. Based on the results of this research, a conclusion was reached to use the van Schilfgaarde equation based K_{sat} in all further analyses in this chapter.

Where drain flow and water table depth measurements are available and/or practical to obtain, K_{sat} estimates made with the van Schilfgaarde equation may provide more reliable modeling results since they take into account the overall effect of backfill, drain spacing and depth, deep percolation, drain pipe parameters, etc.

8.1.2 Objective 2: Hydraulic Conductivity Changes in Backfill

The second objective was to analyze the relative impact of changes in drainage trench backfill properties on runoff and drainage flows. An exponential maximum drain flow equation as a function of year was developed using the maximum drain flow versus year data obtained from the backfill alteration study of Taylor and Fausey (1982). The van Schilfgaarde equation estimated saturated hydraulic conductivity values obtained in the previous analysis were adjusted using this equation over time. Using these adjusted K_{sat} values in DRAINMOD improved the outflow prediction accuracy of the model.

Determining the changes in hydraulic conductivity of backfill for different subsurface drainage system spacings, depths, trench widths, pipe and backfill material properties is considered a major research need. Developing empirical relations for changes in hydraulic conductivity with time, such as Equation 2.15 may not only improve drain flow prediction capability, but improve the use of models like DRAINMOD for drainage system design and evaluation.

8.1.3 Objective 3: Monthly PET Adjustment Factors

The third objective was to evaluate monthly Potential EvapoTranspiration (PET) adjustment factors used in DRAINMOD to predict drain flow and runoff. To determine the monthly PET adjustment factors for North Central Ohio conditions, the estimated monthly Penman-Monteith PET values were divided by the estimated monthly Thornthwaite PET values. Overall, when DRAINMOD was run with these monthly PET adjustment factors, the outflow prediction accuracy of the model worsened. Therefore, until further study is conducted to better warrant their use, a value of 1.0 for the PET adjustment factors was recommended.

If monthly pan or lake evaporation data are available, they could be used to determine monthly PET adjustment factors in place of using the Penman-Monteith equation estimated PET values. In general, if the Thornthwaite daily PET estimates are after all proven not to be appropriate, the water balance algorithms in DRAINMOD have to be checked and tested using the daily Penman-Monteith equation or pan evaporation data.

8.1.4 Objective 4: Evaluation of Kirkham-Hooghoudt Equations on Drain Flow and Runoff Prediction Using DRAINMOD

The last objective was to evaluate the effects of the Kirkham-Hooghoudt equations on drain flow and runoff prediction accuracy with DRAINMOD against an empirical equation, and to determine the relative contribution of the Kirkham equation to drain flow predictions compared to the Hooghoudt equation alone. An assumption was made that the empirical equation (Eq. 2.12) developed by Hoffman (1963) best described the water table depth-drain flow relationship at the experimental site. This equation was then used in place of the Kirkham and Hooghoudt equations to evaluate the effects of the Kirkham-Hooghoudt equations on drain flow and runoff prediction. Overall, the analyses showed that in comparison to drain flow predictions using Equation 2.12, the Kirkham-Hooghoudt equations did not predict drain flows as well, but did predict runoff better than that from simulations using Equation 2.12. In addition, careful selection of a value for the drainage coefficient (DC) is necessary when using the Kirkham-Hooghoudt equations since drain flow predicted by the Kirkham and Hooghoudt equations is limited to the value of DC.

The contribution of the Kirkham equation to drain flows was evaluated using DRAINMOD, with and without the Kirkham equation; or stated another way, with the Kirkham-Hooghoudt equations and the Hooghoudt equation alone. The analyses showed that the addition of the Kirkham equation to the Hooghoudt equation improved drain flow prediction accuracy of DRAINMOD compared to the Hooghoudt equation alone. However, this capability may decrease the runoff prediction accuracy of the model. Again, careful selection of the DC value is important. Based on these results, a decision was made to incorporate the Kirkham equation into the subsurface drainage algorithms of WEPP-WTM model.

Considering the variability of measured outflow results, drain flow predictions by the Kirkham-Hooghoudt solution in DRAINMOD were considered to be satisfactory, as long as it is used with appropriate input parameters such as K_{sat}, DC, and monthly PET factors. However, we also have to consider that some years most of the drain flow and runoff depths measured at the field site were a result of the constant intensity irrigation events. For these irrigation events, the input data for rainfall are equally distributed hourly constant values. These types of constant intensity storms are not seen often in nature. For this reason, if the rainfall measurement interval is less than an hour, using less than hourly time interval rainfall data, such as with the breakpoint option in WEPP, may increase the prediction accuracy of the model. This should be evaluated in future work.

For the overall simulation results using DRAINMOD, when drain flow prediction accuracy improved, runoff prediction accuracy generally worsened. One reason this result may have occured is that in all simulations performed in this study, Green-Ampt infiltration parameters determined by Skaggs et al. (1981) were kept constant. Infiltration rate affects runoff. The values of the Green-Ampt parameters by Skaggs et al. (1981) were based on core method K_{sat} values. Further study is warranted in the selection of Green-Ampt parameter values and the use of various K_{sat} methods for estimating Green-Ampt parameter values. Also, it might be interesting to evaluate the effect of time based adjustments to Green-Ampt parameter values, similar to what was done in this study for backfill effects on K_{sat}.

8.2. Chapter 3. Simulating Water Flow to a Subsurface Drain in Layered Soil

The specific objectives of the work presented in this chapter were: 1) to simulate drain flow into subsurface drainage pipes for a layered soil profile using HYDRUS-2D (Simunek et al., 1996); and 2) to develop an equation similar to that developed by Salem and Skaggs (1998) to predict drain flow rates for transition conditions of the water table for a layered soil. Drain flow and corresponding water table depth data from 1960-1962 were used. In addition, saturated hydraulic conductivity (K_{sat}) values from the core data of Schwab et al. (1963) were used.

The HYDRUS-2D model was used to develop drain flow-water table elevation curves to be compared to the following: i) drain flow-water table relationship described by Hoffman (1963) as the best empirical relationship for the measured drain flow and corresponding midspace water table elevation data from the OARDC site; and ii) the relationship described using the Kirkham and Hooghoudt equations. For this analysis, the drain was represented as a completely permeable half circle with radius equal to the effective radius of the drain. To prevent water entry into the profile from the drain, the boundary represented by the drain was considered as a seepage face with pressure head equal to zero at the beginning of the simulation.

8.2.1 Objective 1: Simulating Drain Flow with HYDRUS-2D

This research was conducted to help determine the ability of the model to predict drain flow-water table elevation relationships. It considered two cases of water loss at the soil surface: with and without evapotranspiration. The model was then used to evaluate the effect of backfill on drain flow-water table depth relationships with and without evapotranspiration.

HYDRUS-2D underpredicted drain flow compared to the empirical and the Kirkham-Hooghoudt equations for water table elevations above 70 cm (27.5 in). However, HYDRUS-2D predictions were very close to those using the empirical and the Kirkham-Hooghoudt equations for water table elevations below 70 cm. There was no difference in the HYDRUS-2D curves for the cases where ET = 0 and for an ET rate of 0.3 cm/day.

There was little difference between the HYDRUS-2D curves for the no backfill simulation and for the backfill simulation used with backfill soil K_{sat} values obtained forty years after installation of the drains at the site. In the backfill simulation scenario, the model produced slightly higher drain flow rates than those obtained without simulating backfill when the midspace water table elevation was greater than 70 cm (27.5 in), but still underpredicted drain flow compared to the empirical and the Kirkham-Hooghoudt equations. To better reflect conductivity values for the backfill in 1960-1962, a range of saturated hydraulic conductivity values within the limits of the undisturbed soil core K_{sat} values published by Schwab et al. (1963) were assigned to the backfill layers. The best HYDRUS-2D results were obtained when a value of 2.54 cm/hr (1 in/hr) was used for all backfill layers. The resulting curve showed substantial improvement in drain flow predictions from HYDRUS-2D especially when the water table elevation was greater than 70 cm. In the range of water table elevations from 70 to 90 cm, the Kirkham-Hooghoudt equations overpredicted drain flow by approximately 82% and HYDRUS-2D underpredicted drain flow by 52%.

Within the scope of the analyses presented above and the available data, objective 1 was met as discussed above. Drain flow-water table elevation curves from HYDRUS illustrated the capability of using HYDRUS-2D to predict drain flows. The drain flow results showed that the HYDRUS-2D model can be used to predict drain flows, at least within the scope of the available input data. No specific limitations in model capability were found. However, there were limitations in model application because of the lack of appropriate input data. Further analysis using backfill K_{sat} values greater than 2.54 cm/hr (1 in/hr) should be performed.

8.2.2 Objective 2: Drain Flow Equation for Transition Conditions of Water Table for a Layered Soil

To develop a new equation similar to that developed by Salem and Skaggs, (1998) for layered soils, a key result must have been met. The equation by Salem and Skaggs was developed by fitting SWMS-2D (Simunek et al., 1994) drain flow results especially for transitional water table conditions that occur between two endpoint conditions: that modeled by the Kirkham equation and that modeled by the Hooghoudt equation.

Modeling the transitional conditions between those covered by the Kirkham equation and those covered by the Hooghoudt equation for a layered soil did not produce the same drain flow values at one endpoint of the transition as was accomplished by Salem and Skaggs (1998). At the lower end of the transition (approximately 70 cm; 27.5 in), HYDRUS-2D was able to produce the same drain flow rate as produced by the Hooghoudt equation. However, at the upper end of the transition (approximately 90 cm; 35.4 in), HYDRUS-2D was not able to produce the same drain flow rates as produced by the Kirkham equation. At this point in the research, an equation similar to that of Salem and Skaggs could not be developed. Further research is recommended, however. This research needs to be conducted using input data from a subsurface drainage experiment site at which drain flows, midspace water table elevations, and saturated hydraulic conductivity values both in the original soil and the backfill are measured at the same time.

8.3. Chapter 4. Evaluation of the Hydrology Component of the WEPP Hillslope Model for Subsurface Drained Cropland

The overall purpose of this work was to gain some assessment of the hydrology component of the WEPP hillslope model (Version 97.3) for cropland with subsurface drainage. The specific objective was to evaluate the runoff, drain flow, and water table depth prediction accuracy of the WEPP hillslope model against measured runoff and drain flow data from Ohio, and predicted water table depths from DRAINMOD (Version 4.6). Three years of measured drain flow and runoff data from the OARDC drainage experiment were used.

Simulations using the WEPP hillslope model were conducted for the years 1969 through 1971. WEPP daily predicted drain flow and runoff values were compared to the measured outflows, and WEPP daily predicted midspace water table depths were compared to those predicted by DRAINMOD. The analyses for drain flow showed that i) drain flow simulation results with WEPP produced very large average deviation values when compared to the measured data; ii) daily drain flows were overpredicted for all storm events, furthermore, large amounts of daily drain flow were predicted at times when there was little or no measured drain flow; and iii) predicted cumulative drain flows at the end of the evaluation season for each year were almost four times larger than the measured drain flows.

The analyses for runoff showed that i) WEPP produced large average deviations between daily predicted and measured runoff depths; ii) WEPP overpredicted runoff for most daily storms, overpredicted cumulative runoff for the evaluation season for all three years. Overprediction of runoff was expected considering the very low values of WEPP predicted baseline effective conductivity.

The analyses of the WEPP predicted midspace water table depth suggest that WEPP may not be truly simulating water table depth. There is no continuous water table depth prediction in WEPP, and its algorithms allow the water table to move quickly between the soil surface and bottom of the soil profile. The calculated standard errors and average deviations between WEPP and DRAINMOD predicted midspace water table depths are very large, in the range of 0.5 to 0.75 m (1.64 to 2.46 ft).

Some of the possible reasons that WEPP drain flow, runoff, and water table depth predictions may be so poor are: the 24 hour time step used to calculate these values in WEPP is large; a large amount of deep seepage from the bottom of the soil profile was simulated by WEPP; WEPP predicted baseline conductivity values appear to be very low especially for use in drain flow calculations for poorly drained cropland; WEPP actually is predicting a perched water table, not a water table produced with saturated conditions from the bottom of the soil profile; and lastly it seems that the soil water content predictions of WEPP throughout the soil profile may not be accurate for subsurface drained cropland. Each of these issues should be researched.

For better drain flow, runoff, water table depth, and soil water content predictions with WEPP, the following suggestions are recommended. The time step should be decreased to some value less than a day, such as an hour. By offering extra input values such as an option whether to simulate deep seepage or not or assign a vertical K_{sat} value with the thickness for impermeable layer, deep seepage can be controlled. As an alternative to the water balance equation used in WEPP, water balance equations used in some more sophisticated models such as DRAINMOD and SWATRE (Belmans et al., 1983) could be used. Input parameters related to prediction of water table depth based on lab or field measurements, such as soil water retention and drained volume capacity should be used in WEPP. The user should be allowed the option to enter saturated hydraulic conductivity data, and use these data in place of the WEPP baseline effective conductivity for the prediction of drain flow. Lastly, the soil water distribution in the soil profile should be related to the true water table depth.

8.4. Chapter 5. Modification of the WEPP Hillslope Model to Incorporate Water Table Management Practices

The WEPP hillslope model (Version 97.3) was modified to help improve the water balance, runoff, drain flow, and water table depth prediction capabilities of WEPP for cropland where water table management systems exist or are planned. The modified model is WEPP-Water Table Management (WTM). Most of the procedures incorporated into the modified water balance algorithms were taken from DRAINMOD. Predicted PET, plant root depth, depressional storage depth, and saturated hydraulic conductivity adjustments for frozen soils from WEPP were retained. Upward flux rate from the water table was calculated using the concept of matrix flux potential by Memon et al. (1986). The estimated runoff related sediment yield was predicted using the erosion prediction components of the WEPP hillslope model.

WEPP-WTM predicts hourly runoff, drain flow, subirrigation flow, controlled drainage and subirrigation excess flows, water table depth, and daily sediment yields from the fields on which any of the water table management practices (or any combination of these) is planned or present. Daily outputs are presented in the water balance output file of WEPP-WTM.

WEPP-WTM offers options to the user to use field or lab measured soil water retention data, water table depth-upward flux and drained volume data, saturated hydraulic conductivity of soil layers, and daily PET values. The model also allows the user to control deep seepage and depressional storage depth.

The developed WEPP-WTM can be used especially for slightly sloped field sized areas at which subsurface lateral water lost from the soil profile is negligible. In addition, this model was developed for humid regions where the water table is close to the soil surface most of the year.

8.5. Chapter 6. Field Testing of the WEPP Water Table Management (WEPP-WTM) Model for Subsurface Drained Cropland

The purpose of this work was to evaluate the performance of the Water Erosion Prediction Project-Water Table Management (WEPP-WTM) model in simulating runoff, drain flow, and water table depth for subsurface drained cropland conditions. The runoff, drain flow, and daily water table depth prediction accuracy of WEPP-WTM for field sized areas was tested against field measured data from two sites. Three years (1969, 1970, and 1971) of field data obtained from the OARDC North Central Ohio site were used for testing the drain flow and runoff predictions. There were no continuous water table depth measurements at the OARDC site. Water table depth predictions were evaluated against a five year field data set from Aurora, North Carolina (Skaggs, 1978).

The analysis of WEPP-WTM using constant and adjusted van Schilfgaarde equation estimated K_{sat} values indicated that using the adjusted saturated horizontal hydraulic conductivity (K_{sat}) values generally improved the drain flow prediction accuracy of the model while it decreased the runoff prediction accuracy of the model.

Overall, WEPP-WTM produced drain flow and runoff results similar to those from DRAINMOD. The WEPP-WTM model produced average deviations for drain flow that were better than all of those obtained with WEPP and in most cases better than those obtained with

DRAINMOD. However, runoff predictions from WEPP-WTM were similar, but poorer than those obtained from DRAINMOD, but much better than those from WEPP.

To evaluate the water table depth prediction accuracy of WEPP-WTM, standard errors were compared with those obtained from published results using DRAINMOD, ADAPT, and SWATREN for the Aurora, North Carolina site. Overall, the predictions of water table depth from WEPP-WTM were very comparable to those from the other models. The ranked overall mean of the standard errors for all three drain spacings from the DRAINMOD 1, ADAPT 1, DRAINMOD 2, ADAPT 2, WEPP-WTM, and SWATREN water table depth predictions were 14.65, 16.87, 17.27, 17.47, 17.85, and 18.42 cm (5.77, 6.64, 6.80, 6.88, 7.03, and 7.25 in), respectively. The overall mean of the average deviations from all the models except DRAINMOD 1 was 14 cm (5.5 in). For DRAINMOD 1, an average deviation of 11.4 cm (4.5 in) was calculated from the values given by Skaggs (1978 and 1982).

The runoff related sediment yield prediction capability of WEPP-WTM was not tested, and therefore, testing this component is needed.

For this evaluation, WEPP-WTM was tested against data from individual plots and field sized areas. The WEPP watershed model (Ascough II et al., 1997) should now be evaluated for watershed scale capability after WEPP-WTM model is connected with it.

The WEPP-WTM model does not simulate preferential flow to the drains through cracks which can occur in clayey soils during hot summer months or other day periods. Algorithms simulating preferential flow could be added to the model and evaluated, possibly on conditions similar to those evaluated by Workman and Skaggs (1990 and 1991) with PREFLO.

The WEPP-WTM model was developed for humid regions. For the possible use of the model for semi arid regions, the runoff prediction of the model for these regions should to be tested.

The time lag between a rise in the ditch water level (weir depth changes) and the midspace water table response may be a problem in modeling subirrigation. This time lag could possibly by evaluated using the HYDRUS-2D model (Simunek et al., 1996). The effect of the time lag could then be incorporated into the water table depth prediction algorithms of WEPP-WTM and then evaluated.

8.6. Chapter 7. Using WEPP-WTM Model for the DARA WRSIS Watershed

The overall purpose of the research presented in this chapter was to evaluate the WEPP-WTM model for one of the WRSIS field sites. The specific objectives were: a) prepare input data to be used with the WEPP-WTM linked WEPP watershed model for predicting runoff volumes entering the wetland of the DARA WRSIS site; and b) compare runoff volumes predicted by the linked model with measured runoff volumes for a seven month time period in 1999.

Most of the input data except horizontal saturated hydraulic conductivity values for the linked model were prepared.

A seven month period is a short time to evaluate a watershed model, especially when only two months of flow measurements are valid. In addition, the horizontal saturated hydraulic conductivity values obtained using the velocity permeameter were used in the model, and these values are considered low compared to visual observations of watertable depths and flows at the site. Therefore, further conductivity tests should performed and the model reevaluated. Lastly, because of the unavailable of field measured drain flows, subirrigation flows, water table depths, and sediment yields, these values could not be evaluated.

8.7. REFERENCES

Ascough II, J.C., C. Baffaut, M.A. Nearing and B.Y. Liu. 1997. The WEPP watershed model: I. Hydrology and erosion. Transactions of the ASAE 40(4):921-933.

Belmans, C., J.G. Wesseling and R.A. Feddes. 1983. Simulation model of the water balance of a cropped soil: SWATRE. J. Hydrology 63(1983):271-286.

Brown, L.C., B.J. Czartoski, N.R. Fausey and H.W. Belcher. 1998. Constructed wetland and subirrigation linkage provides high yield potential and environmentally sound corn and soybean production systems. 524-530. In Proc. of the 7'th International Drainage Symposium. ed. L.C. Brown. ASAE. 738 p.

Flanagan, D.C. and M.A. Nearing (Eds.). 1995. WEPP technical documentation. NSERL Report No. 10, USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, Indiana. 284 p.

Hoffman, G.J. 1963. Tile flow from a stratified anisotropic soil with a falling water table. Master Thesis. Ohio State University, Columbus, Ohio. 83 p.

Memon, N.A., C.A. Madramootoo, S.O. Prasher and R.S. Broughton. 1986. A method for estimating the steady upward flux from a water table. Transactions of the ASAE 29(6):1646-1649.

Salem, H.E. and R.W. Skaggs. 1998. Predicting drainage rates under varying water table conditions. 168-175. In Proc. of the 7'th International Drainage Symposium. ed. L.C. Brown. ASAE. 738 p.

Schwab, G.O., T.J. Thiel, G.S. Taylor and J.L. Fouss. 1963. Tile and surface drainage of clay soils. Research Bulletin 935. Ohio Agricultural Experiment Station, Wooster, Ohio. 47 p.

Schwab, G.O., N.R. Fausey and C.R. Weaver. 1975. Tile and surface drainage of clay soils. Research Bulletin 1081. Ohio Agricultural Research and Development Center, Wooster, Ohio. 37 p.

Schwab, G.O., N.R. Fausey, E.D. Desmond and J.R. Holman. 1985. Tile and surface drainage of clay soils. Research Bulletin 1166. Ohio Agricultural Research and Development Center, Wooster, Ohio. 29 p.

Simunek, J., T. Vogel and M. Th. van Genuchten. 1994. The SWMS_2D Code for Simulating Water Flow and Solute Transport in Two –Dimensional Variably Saturated Media. Ver. 1.21. Research Report No. 132. U.S. Salinity Laboratory, Agricultural Research Service, USDA, Riverside, California. 197 p.

Simunek, J., M. Sejna and M. Th. van Genuchten. 1996. Ground water modeling software HYDRUS-2D. Simulating water flow and solute transport in two-dimensional variably saturated media. IGWMC-TPS 53. Ver. 1.0 U.S. Salinity Laboratory, Agricultural Research Service, USDA, Riverside, California. 167 p.

Skaggs, R.W. 1978. A water management model for shallow water table soils. Report No. 134. Raleigh, North Carolina. Water Resources Research Institute, Univ. of North Carolina. 175 p.

Skaggs, R.W. 1982. Field evaluation of a water management simulation model. Transactions of the ASAE 25(3):666-674.

Skaggs, R.W., N.R. Fausey and B.H. Nolte. 1981. Water management model evaluation for North Central Ohio. Transactions of the ASAE 24(4):922-928.

Taylor, G.S. and N.R. Fausey. 1982. Backfill alterations and drainage of clay soils. 139-148. In Proc. of the 4'th International Drainage Symposium. ed. G.J. Kriz. ASAE. 177 p.

Workman, S.R. and R.W. Skaggs. 1990. PREFLO: A water management model capable of simulating preferential flow. Transactions of the ASAE 33(6):1939-1948.

Workman, S.R. and R.W. Skaggs. 1991. Evaluation of the water management model. PREFLO. Transactions of the ASAE 34(5):2053-2059.

LIST OF REFERENCES

Abtew, W., M.J. Chimney, T. Kosier, M. Guardo, S. Newman and J. Obeysekera. 1995. The everglades nutrient removal project: A constructed wetland designed to treat agricultural runoff /drainage. 45-55, In Proc. Versatility of Wetlands in the Agricultural Landscape. ed. K.L. Campbell. AWRA and ASAE. 756 p.

Alberts, E.E., M.A. Nearing, M.A. Weltz, L.M. Risse, F.B. Pierson, X.C. Zhang, J.M. Laflen and J.R. Simanton. 1995. Chapter 7. Soil component. 7.1-7.47. In WEPP technical documentation. Eds. Flanagan, D.C. and M.A. Nearing. NSERL Report No. 10. West Lafayette, Indiana. 248 p.

Allen, R.G. 1990. REF-ET reference evapotranspiration calculator manual, Ver. 2.0. Utah State University Foundation, Utah State Univ., Logan, Utah. 12 p.

Allen, R.G. 1994. REF-ET reference evapotranspiration calculation software, Ver. 2.15a. Utah State University Foundation, Utah State Univ., Logan, Utah. 42 p.

Amatya, D. M., R.W. Skaggs and J.D. Gregory. 1992. Comparison of methods for estimating potential evapotranspiration. ASAE Paper No. 92-2630. St. Joseph, Mich.: ASAE. 27 p.

Amatya, D. M., R.W. Skaggs and J.D. Gregory. 1995. Comparison of methods for estimating REF-ET. J. Irrigation and Drainage Engineering, ASCE 121(6):427-435.

Amoozegar, A. and A.W. Warrick. 1986. Hydraulic conductivity of saturated soils: Field Methods. p:735-768. In A. Klute (Ed.). Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods. SSSA Book Series: 5 (formerly Agronomy Monograph 9). Madison, Wisconsin. 1188 p.

Arnold, J.G., M.A. Weltz, E.E. Alberts and D.C. Flanagan. 1995. Chapter 8. Plant growth component. 8.1-8.41. In WEPP technical documentation. Eds. Flanagan, D.C. and M.A. Nearing. NSERL Report No. 10. West Lafayette, Indiana. 248 p.

Ascough II, J.C., C. Baffaut, M.A. Nearing and B.Y. Liu. 1997. The WEPP watershed model: I. Hydrology and Erosion. Transactions of the ASAE 40(4):921-933.

ASHRAE Handbook. 1993. Fundamentals, I-P Edition. American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc. Atlanta, GA.

Backlund, V.L., E.A. Ross, P.H. Willey, T.L. Spofford and D.M. Renner. 1995. Effect of agricultural drainage on water quality in humid portion of Pacific Northwest. J. Irrigation and Drainage Engineering, ASCE 121(4):289-291.

Baffaut, C., M.A. Nearing, J.C. Ascough II and B.Y. Liu. 1997. The WEPP watershed model: II. Sensitivity analysis and discretization on small watershed. Transactions of the ASAE 40(4):935-943.

Baker, D.B. 1993. The Lake Erie agroecosystem program: water quality assessments. Agriculture, Ecosystems and Environment. 46(1993):197-215.

Baumer, Otto W. 1989. Predicting unsaturated hydraulic parameters. p.341:354. In M. Th. van Genuchten and F.J. Leij, and L.J. Lund (Eds.) Proceedings of the international workshop on indirect methods for estimating the hydraulic properties of unsaturated soils. Riverside, California, October 11-13. U.S. Dept. of Agriculture: Dept. of Soil and Environmental Sciences, University of California, c1992. 718 p.

Belcher, H.W. and B.W. Fehr. 1990. Performance of a subirrigation automation system. ASAE Paper No. 902607. St. Joseph, Mich.: ASAE. 6 p.

Belcher, H.W. and L.J. Protasiewicz. 1991. Water quality impact of subirrigating maize. 281-298. In Subirrigation and Controlled Drainage. eds. H.W. Belcher and F.M. D'Itri. Ann Arbor, Michigan, Lewis Publishers. 482 p.

Belmans, C., J.G. Wesseling and R.A. Feddes. 1983. Simulation model of the water balance of a cropped soil: SWATRE. J. Hydrology 63(1983):271-286.

Bengston, R.L., C.E. Carter, H.F. Morris and J.G. Kowalczuk. 1984. Reducing water pollution with subsurface drainage. Transactions of the ASAE 27(1):80-83.

Bengston, R.L., C.E. Carter, J.L. Fouss, L.M. Southwick and G.H. Willis. 1995. Agricultural drainage and water quality in Mississippi Delta. J. Irrigation and Drainage Engineering, ASCE 121(4):292-295.

Borg, H. and D.W. Williams. 1986. Depth development of roots with time: An empirical description. Transactions of the ASAE 29(1):194-197.

Bouwer, H. and R.D. Jackson. 1974. Determining soil properties, section X. p.611-666. In J. van Schilfgaarde (Ed.). Drainage for Agriculture. Agronomy No. 17. American Society of Agronomy. Madison, Wisconsin. 700 p.

Broughton, S.R. and C.A. Madramootoo. 1991. Effects of four water table depths on soybean yields. 97-110. In Subirrigation and Controlled Drainage. eds. H.W. Belcher and F.M. D'Itri. Ann Arbor, Michigan, Lewis Publishers. 482 p.

Brown, L.C., A. Ward and N.R. Fausey. 1997. Agricultural water table management systems. Extension Fact Sheet AEX 321-97. The Ohio State University Extension, Columbus. 8 p.

Brown, L.C., B.J. Czartoski, N.R. Fausey and H.W. Belcher. 1998. Constructed wetland and subirrigation linkage provides high yield potential and environmentally sound corn and soybean production systems. 524-530. In Proc. of the 7'th International Drainage Symposium. ed. L.C. Brown. ASAE. 738 p.

Chester, P.W. and D. Riethman. 1997. Runoff storage requirements for a closed-loop sub-irrigation system. ASAE Paper No. 972132. St. Joseph, Mich.: ASAE. 8 p.

Alexander, C.A. 1988. ADAPT – A model to simulate pesticide movement into drain tiles. Master of Science Thesis. Ohio State University, Columbus. 241 p.

Chung, S.O., A.D. Ward and C.W. Schalk. 1992. Evaluation of the hydrologic component of the ADAPT water table management model. Transactions of the ASAE 35(2):571-579.

Crumpton, W.G. and J.L. Baker. 1993. Integrating wetlands into agricultural drainage systems: Predictions of nitrate loading and loss in wetlands receiving agricultural subsurface drainage. 118-126. In Proc. Integrated Resource Management and Landscape Modification for Environmental Protection. ed. J. Kent Mitchell. Chicago, Illinois. ASAE. 387 p.

Czartoski, B.J., N. Fausey, L. C. Brown and R.L. Cooper. 1997. Maumee Valley Resource Conservation & Development Area Quality Assurance Plan, Defiance, Ohio.

Czartoski, J., L.C. Brown, N.R. Fausey, A.M. Brate, H.W. Belcher and R.L. Cooper. 1995. Marketing wetland for profit. 367-372. In Proc. Versatility of Wetlands in the Agricultural Landscape. ed. K.L. Campbell. AWRA and ASAE. 756 p.

De Laney, T.A. 1995. Benefits to downstream flood attenuation and water quality as a result of constructed wetlands in agricultural landscapes. J. Soil and Water Conservation 50(6):620-626.

Deer-Ascough, L.A., G.A. Weesies, J.C. Ascough II, J.M. Laflen. 1995. Plant Parameter Database for Erosion Prediction Models. 1995. Applied Engineering in Agriculture. ASAE 11(5):659-666

Desmond, E.D., A.D. Ward, N.R. Fausey and S.R. Workman. 1995. Comparison of daily water table depth prediction by four simulation models. Transactions of the ASAE 39(1):111-118.

Dumm, L.D. 1954. Drain spacing formula. Agricultural Engineering 35(10):726-730.

Ernst, L.F. 1962. Grondwaterstromingen in de verzadigde zone en hun berekening bij aanwezigheid van horizontale evenwijdige open leidingen. Versl. Landbouwk. Onderz. 67-15. Pudoc, Wageningen. 189 p.

Evans, R.O. and R.W. Skaggs. 1996. Operating controlled drainage and subirrigation systems. Publication Number: AG 356, North Carolina Cooperative Extension Service. North Carolina State University. 7 p.

Evans, R.O., R.W. Skaggs and J. W. Gilliam. 1995. Controlled versus conventional drainage effects on water quality. J. Irrigation and Drainage Engineering, ASCE 121(4):271-276.

Evans, R.O., R.W. Skaggs and R.E. Sneed. 1996. Economics of controlled drainage and subirrigation systems. Publication Number. AG 397, North Carolina Cooperative Extension Service. North Carolina State University. 23 p.

Fausey, N.R. 1975. Numerical model analysis and field study of shallow subsurface drainage. Ph.D. Thesis. Ohio State University, Columbus, Ohio. 147 p.

Fausey, N.R. 1977. Flow to shallow drain tubes in layered soils. 58-60. In Proc. of the 3'rd International Drainage Symposium. ASAE. 149 p.

Fausey, N.R. 1994. Subirrigation/drainage systems for water table management in the Midwest. 242-246. In Proc. 15'th International Irrigation Exposition and Technical Conference, Atlanta, Georgia. The Irrigation Association. 280 p.

Fausey, N.R. 1999. Personal communication. Research leader, USDA-ARS Soil Drainage Research Unit, Columbus, Ohio.

Fausey, N.R. and R.L. Cooper. 1991. Subirrigation response of soybeans grown with high yield potential management. 225-230. In Subirrigation and Controlled Drainage. eds. H.W. Belcher and F.M. D'ltri. Ann Arbor, Michigan, Lewis Publishers. 482 p.

Fausey, N.R., L.C. Brown, H.W. Belcher and R.S. Kanwar. 1995. Drainage and water quality in Great Lakes and Cornbelt States. J. Irrigation and Drainage Engineering, ASCE 121(4):283-288.

Feddes, R.A., P.J. Kowalik and H. Zaradyn. 1978. Simulation of field water use and crop yield. Simulation Monographs. Wageningen, the Netherlands: PUDOC.

Fipps, G., R.W. Skaggs and J.L. Nieber. 1986. Drains as a boundary condition in finite elements. Water Resource Research 22(11):1613-1621.

Flanagan, D.C. and M.A. Nearing (Eds.). 1995. WEPP technical documentation. NSERL Report No. 10, USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, Indiana. 284 p.

Flanagan, D.C. and S. J. Livingston (Eds). 1995. WEPP user summary. NSERL Report No. 11, USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, Indiana. 131 p.

Fouss, J.L., R.L. Bengtson and C.E. Carter. 1987. Simulating Subsurface Drainage in the Lower Mississippi Valley with DRAINMOD. Transactions of the ASAE 30(6):1679-1688.

Grant, D.M. and B.D. Dawson, 1997. Isco Open Channel Flow Measurement Handbook.Lincoln, NE. 501 p.

Green, W.H. and Ampt, G.A. 1911. Studies on soil physics. I. Flow of air and water through soils. J. Agricultural Science 4(Part I):1-24.

Hammad, H.Y. 1962. Depth and spacing of tile drain systems. ASCE Proceedings 88(IR1):15-34.

Hammer, D.A. 1992. Creating Freshwater Wetlands, Lewis Publishers, Inc., Chelsea, Michigan. 298 p.

Harrold, L.L. and F.R. Dreibelbis. 1958. Evaluation of agricultural hydrology by monolith lysimeters. Tech. Bull. No. 1179. USDA-Ohio Agricultural Experiment Station. Washington, D.C. 166 p.

Hess, T.M. 1999. Reference Evapotranspiration (Ver. 2)[DAILYET], Cranfield University, Silsoe, UK.

Hoffman, G.J. and G.O. Schwab. 1964. Tile spacing prediction based on drain outflow. Transactions of the ASAE 7(4):444-447.

Hoffman, G.J. 1963. Tile flow from a stratified anisotropic soil with a falling water table. Master of Science Thesis. Ohio State University. Columbus, Ohio. 83 p.

Holmgren, G.S., R.L. Juve, and R.C. Geschwender. 1977. Amechanically controlled variable-rate leaching device. Soil Science Society of America Journal. 41(6):1207-1208.

Hooghoudt, S.B. 1940. Algemeene beschouwing van het probleem van de detailontwatering en de infiltratie door middel van parallel loopende drains, greppels, slooteen, en kanalen. Versl. Landbouwk. Onderz. 46(14)B. Algemeene Landsdrukkerij, 's-Gravenhage, 193 p.

Hothem, J. H. 1999. Modeling of flow-routing in a linked wetland-reservoir-subirrigation system (WRSIS) using Simulink. Master of Science Thesis. Ohio State University. Columbus, Ohio. 263 p.

Istok, J.D. and G.F. Kling. 1983. Effect of subsurface drainage on runoff and sediment yield from an agricultural watershed in Western Oregon, U.S.A. J. Hydrology 65(1983):279-291.

James, L.G. 1993. Principles of Farm Irrigation System Design. Krieger publishing company, Malabar, Florida. 543 p.

Jensen, M.E. (Ed.). 1974. Consumptive use of water and irrigation requirements. Rep.Tech. Com. on Irrig. Water Requirements, Irrig. and Drain. Div. ASCE. 227 pp.

Jensen, M.E., R.D. Burman and R.G. Allen (Eds). 1990. Evapotranspiration and Irrigation Water Requirements. ASCE Manual and Reports on Engineering Practice No. 70. ASCE. New York, USA. 335 p.

Kadlec, R.H. and R.L. Knight (Eds). 1995. Treatment Wetlands. New York, Lewis Publishers. 893 p.

Kaluarachchi, J.J. and J.C. Parker. 1987. Finite element analysis of water flow in variably saturated soil. J. Hydrology 90(1987):269-291.

Kilmer, V.J. and L.T. Alexander. 1949. Methods of making mechanical analysis of soils. Soil Science 68(July-December):15-24.

Kirkham, D. 1957. II. Theory of land drainage, III. The ponded water case. p:139-181. In J. N. Luthin (Ed.). Drainage of Agricultural Lands. Agronomy Monograph No. 7, American Society of Agronomy, Madison, Wisconsin. 620 p.

Klute, A. and C. Dirksen. 1986. Hydraulic conductivity and diffusivity: Laboratory methods. p:687-732. In A. Klute (Ed.). Methods of Soil Analysis. Part I. Physical and Mineralogical Methods. SSSA Book Series: 5 (formerly Agronomy Monograph 9). Madison, Wisconsin. 1188 p.

Konyha, K.D, R.W. Skaggs and J.W. Gilliam. 1992. Effects of drainage and water-management practices on hydrology. J.Irrigation and Drainage Engineering, ASCE 118(5):807-819.

Kowald, R. 1968. Technische, hydraulische und bodenkundliche probleme der tonrohrdranun ginsbesondere in Marschgebieten. Habilitationsschrift, Universitat Giessen (cited as by Trafford and Rycroft, 1974).

Laflen, J. M. 1999. Personal communication. Agricultural Engineer, USDA-Agricultural Research Service. USDA Soil Tilth Center Ames, Iowa.

Lal, R. 1997. Soil Science 671. Soil Physics Practical Manual. Ohio State University. 78 p.

Lane, L.J. and M.A. Nearing (Eds.). 1989. USDA-Water erosion prediction project: Hillslope profile model documentation. NSERL Rep. No. 2, USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, Indiana. 265 p.

LeCureux, J.P. 1991. Profitability of a crop rotation utilizing subirrigation. 193-205. In Subirrigation and Controlled Drainage. eds. H.W. Belcher and F.M. D'Itri. Ann Arbor, Michigan, Lewis Publishers. 482 p.

Leonard, R.A., W.G. Knisel and D.A. Still. 1987. GLEAMS: Groundwater loading effects of agricultural management systems. Transactions of the ASAE 30(5):1403-1418.

Liu, B.Y., M.A. Nearing, C. Baffaut and J.C. Ascough II. 1997. The WEPP watershed model: III. Comparisons to measured data from small watersheds. Transactions of the ASAE 40(4):945-952.

Martinez, M.A., E.J. Monke and E.J. Kladivko. 1989. Drain flow simulation using finite element technique. ASAE Paper No. 89-2099. St. Joseph, Mich.: ASAE. 19 p.

Maumee Valley Resource Conservation and Development (MVRCD). 1994. Area Marketing Wetlands for Profit Work Plan, USDA-NRCS, MVRCD Area Office. 06825 St. Rt. 66 N, Suite C. Defiance Ohio 43512. 19 p.

Melvin, S.W. and R.S. Kanwar. 1991. Environmental and economic impacts of a recycling subirrigation drainage system. 315-326. In Subirrigation and Controlled Drainage. eds. H.W. Belcher and F.M. D'Itri. Ann Arbor, Michigan, Lewis Publishers. 482 p.

Memon, N.A., C.A. Madramootoo, S.O. Prasher and R.S. Broughton. 1986. A method for estimating the steady upward flux from a water table. Transactions of the ASAE 29(6):1646-1649.

Merva, G.E., L. Segerlind, H. Murase and N.R. Fausey. 1983. Finite element modeling for depth and spacing of drains in layered soils. Transactions of the ASAE 26(2):452-456.
Methods. p:735-768. In A. Klute (Ed.). Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods. SSSA Book Series: 5 (formerly Agronomy Monograph 9). Madison, Wisconsin. 1188 p.

Millington, R.J. and J.P. Quirk. 1959. Permeability of porous media. Nature 183(4658):387-388.

Mitsch, W.J. and J.G. Gosselink. 1993. Wetlands. New York, Van Nostrand Reinhold. 722 p.

Mohammad, F. S. 1978. Evaluation of methods for predicting potential evapotranspiration in humid regions. Master of Science Thesis. North Carolina State University, Raleigh, North Carolina. 93 p.

Monteith, J.L. 1981. Evaporation and surface temperature. Quarterly J. Royal Meteorological Society 107(451):1-27.

Moody, W.T. and F. Asce. 1966. Nonlinear differential equation of drain spacing. J. Irrigation and Drainage Engineering, ASCE 92(IR2):1-9.

Nearing, M.A., D.I. Page, J.R. Simanton and L.J. Lane. 1989. Determining erodibility parameters from rangeland field data for a process-based erosion model. Transactions of the ASAE 32(3):919-924.

Nokes, S.E. 1995. Evapotranspiration, Chapter 4, p:91-132. In Ward A. D. and W.J Elliot (Eds). Environmental Hydrology. Lewis Publishers. New York, USA. 462 p.

Ohio Soil Survey. 1960. Auger hole percolation tests conducted by Jim Evans and Ken Donaldson from the field experiment notes of the drainage experiment at the Ohio Agricultural Research and Development Center, North Central Branch, near Sandusky, Ohio.

Oztekin, T., N.M. N'Jie, J. Hothem, L. Luckeydoo, L.C. Brown, N.R. Fausey, B.J. Czartoski, and G. Mills. 1998. Monitoring system for water quality and quantity, and ecological parameters at the DARA wetland-reservoir subirrigation system site. An ASAE Presentation Paper No. 98-2110.

Patterson, J.M., B.C. Atherton, L. Tornes, R.M. Gehring, J.R. Steiger, J.J. Prenger, L.C. Brown, T.L. Zimmerman, G. Hall and N.R. Fausey. 1997. Modeling drainage response and recommendations for a modern agricultural water management guide. ASAE Paper No. 972125. St. Joseph, Mich.: ASAE. 20 p.

Peech, M.L., A. Dean, and J.F. Reed. 1947. Methods of soil analysis for soil-fertility investigations. USDA Circular No. 757. U.S. Government Printing Office, Washington, D.C.

Penman, H.L. 1963. Vegetation and Hydrology. Tech. Com. No. 53, Commonwealth Bureau of Sols, Harpenden, England. 125 p.

Pickens, J.F., R.W. Gillham and D.R. Cameron. 1979. Finite element analysis of the transport of water and solutes in tile-drained soils. J. Hydrology 40(1979):243-264.

Post, G.J. 1956. A study of three methods for determination of organic carbon in Ohio soils of several great groups and the profile distribution of carbon-nitrogen ratios. M.S. Thesis, The Ohio State University.

Priestly, C.H.B. and R.J. Taylor. 1972. On the assessment of surface heat flux and evaporation using large scale parameters. Monthly Weather Review 100(2):81-92

Reyes, M.R., R.L. Bengston and J.L. Fouss. 1994. GLEAMS-WT hydrology submodel modified to include subsurface drainage. Transactions of the ASAE 37(4):1115-1120.

Richards, L.A. 1931. Capillary conduction of liquids through porous mediums. Physics 1(1):318-333.

Ritter, W.F., R.P. Rudra, P.H. Milburn and S. Prasher. 1995. Drainage and water quality in Northern United States and Eastern Canada. J. Irrigation and Drainage Engineering, ASCE 121(4):296-301.

Ritzema, H.P. (Ed.). 1994. Drainage Principles and Applications. ILRI Publication 16.
Riverside, California. 167 p.
Riverside, California. 167 p.
Robertson, L.S., E.H. Kidder, A.E. Erickson and D.L. Mokma. 1979. Tile drainage for improved crop production. Extension Bulletin E-909. Cooperative Extension Service, Michigan State University, East Lansing, Michigan. 11 p.

Rogers, J.S. and J.L. Fouss. 1989. Hydraulic conductivity determination from vertical and horizontal drains in layered soil profiles. Transactions of the ASAE 32(2):589-595.

Rogers, J.S., H.M. Selim and J.L. Fouss. 1995. Comparison of drainage under steady rainfall versus falling water table conditions. Soil Science 160(6):391-399.
runoff and soil loss predictions using natural runoff plot data. Transactions of the ASAE 39(3):855-863.

Sabbagh, G.J., J.L. Fouss and R.L. Bengston. 1993. Comparison of EPIC-WT and DRAINMOD simulated performance of land drainage system. Transactions of the ASAE 36(1):73-79.

Salem, H.E. and R.W. Skaggs. 1998. Predicting drainage rates under varying water table conditions. 168-175. In Proc. of the 7'th International Drainage Symposium. ed. L.C. Brown. ASAE. 738 p.

Savabi, M.R. and J.R. Williams. 1995. Chapter 5. Water balance and percolation. 5.1-5.14. In WEPP technical documentation. Eds. Flanagan, D.C. and M.A. Nearing. NSERL Report No. 10. West Lafayette, Indiana. 248 p.

Savabi, M.R., 1993. Modeling subsurface drainage and surface runoff with WEPP. J. of Irrigation and Drainage Engineering, ASCE 119(4):801-813.

Savabi, M.R., D.C. Flanagan, B. Hebel and B.A. Engel. 1995a. Application of WEPP and GIS-GRASS to a small watershed in Indiana. J. Soil and Water Conservation 50(5): 477-483.

Savabi, M.R., R.W. Skaggs and C.A. Onstad. 1995. Chapter 6. Subsurface hydrology. 6.1-6.14. In WEPP technical documentation. Eds. Flanagan, D.C. and M.A. Nearing. NSERL Report No. 10. West Lafayette, Indiana. 248 p.

Schwab, G.O., D. D. Fangmeier, W. J. Elliot, and R. K. Frevert. 1993. Soil and Water Conservation Engineering. John Wiley & Sons, Inc., New York. 507 p.

Schwab, G.O., N.R. Fausey and C.R. Weaver. 1975. Tile and surface drainage of clay soils. Research Bulletin 1081. Ohio Agricultural Research and Development Center, Wooster, Ohio. 37 p.

Schwab, G.O., N.R. Fausey, E.D. Desmond and J.R. Holman. 1985. Tile and surface drainage of clay soils. Research Bulletin 1166, Ohio Agricultural Research and Development Center, Wooster, Ohio. 29 p.

Schwab, G.O., T.J. Thiel, G.S. Taylor and J.L. Fouss. 1963. Tile and surface drainage of clay soils. Research Bulletin 935. Ohio Agricultural Experiment Station, Wooster, Ohio. 47 p.

Segerlind, L.J. 1976. Applied Finite Element Analysis. John Wiley & Sons, NY. 422 p.

Shaykewich, C.F. and L. Stroosnijder. 1977. The concept of matric flux potential applied to simulation of evaporation from soil. Neth. J. Agric. Sci. 25:63-82.

Shirmohammadi, A., R.D. Wenberg, W.F. Ritter and F.S. Wright. 1995. Effect of agricultural drainage on water quality in Mid-Atlantic States. J. Irrigation and Drainage Engineering, ASCE 121(4):302-307.

Simunek, J. 1998. Personal communication. U.S. Salinity Laboratory, Agricultural Research Service, USDA, Riverside, California.

Simunek, J., M. Sejna and M. Th. van Genuchten. 1996. Ground water modeling software HYDRUS-2D. Simulating water flow and solute transport in two-dimensional variably saturated media. IGWMC-TPS 53. Ver. 1.0 U.S. Salinity Laboratory, Agricultural Research Service, USDA, Riverside, California. 167 p.

Simunek, J., T. Vogel and M. Th. van Genuchten. 1994. The SWMS_2D Code for Simulating Water Flow and Solute Transport in Two –Dimensional Variably Saturated Media. Ver. 1.21.

Research Report No. 132. U.S. Salinity Laboratory, Agricultural Research Service, USDA, Riverside, California. 197 p.

Skaggs, R.W. 1976. Determination of the hydraulic conductivity-drainable porosity ratio from water table measurements. Transactions of the ASAE 19(1):73-80; 84.

Skaggs, R.W. 1978. A water management model for shallow water table soils. Report No. 134. Raleigh, NC. Water Resources Research Institute, Univ. of North Carolina. 175 p.

Skaggs, R.W. 1980. DRAINMOD Reference Report. Methods for design and evaluation of drainage-water management systems for soils with high water tables. North Carolina State University, Raleigh, North Carolina. 177 p.

Skaggs, R.W. 1982. Field evaluation of a water management simulation model. Transactions of the ASAE 25(3):666-674.

Skaggs, R.W., M.A. Breve and J.W. Gilliam. 1994. Hydrologic and water quality impacts of agricultural drainage. Critical Reviews in Environmental Science and Technology, CRC Press, Inc. 24(1):1-32.

Skaggs, R.W., N.R. Fausey and B.H. Nolte. 1981. Water management model evaluation for North Central Ohio. Transactions of the ASAE 24(4):922-928.

Smith, M.C., R.W. Skaggs and J.E. Parsons. 1985. Subirrigation system control for water use efficiency. Transactions of the ASAE 28(2):489-496.

Soil Survey Staff. 1972. Soil Survey Laboratory Methods and Procedures for Collecting Soil Samples. Soil Survey Investigations Report No. 1. USDA Soil Conservation Service. U.S. Govt. Printing Office, Washington D.C.

Stuart D.G., L.C. Brown, D.L. Risley and D.L. Conrad. 1992. Ohio's wetland inventory. ASAE Paper No. 92-2120. St. Joseph, Mich.: ASAE. 10 p.

Tan, C.S., C.F. Drury, M. Soultani, H.Y.F. Ng, I.J. van Wesebeeck, J.D. Gaynor and T.W. Welacky. 1998. Controlled drainage and Subirrigation effects on crop yields and water quality. 676-683. In Proc. of the 7'th International Drainage Symposium. ed. L.C. Brown. ASAE. 738 p.

Taylor, G.S. and N.R. Fausey. 1982. Backfill alterations and drainage of clay soils. p:139-148.In Kriz, G.J. (Ed.). Procedings of the Fourth National Drainage Symposium, ASAE, Chicago, Illinois. 177 p.

Taylor, G.S., E. Stibbe, T.J. Thiel and J.H. Jones. 1970. Hydraulic conductivity profiles of Toledo and Miami Soils as measured by field monoliths. Research Bulletin. 1025. Ohio Agricultural Research and Development Center, Wooster, Ohio. 17 p.

Taylor, S.A. and G.L. Ashcroft. 1972. Physical Edaphology. The physics of irrigated and non-irrigated soils. W.H. Freeman and Company, San Francisco, pp. 533.

Teague, L.L., A.L.Kenimer, B.J. Lesikar and F.L. Mitchell. 1997. Constructed wetlands for the control of agricultural nonpoint source pollution. ASAE Paper No. 972037. St. Joseph, Mich.: ASAE. 7 p.

Thomas, D.L., C.D. Perry, R.O. Evans, F.T. Izuno, K.C. Stone and J.W. Gilliam. 1995. Agricultural drainage effects on water quality in Southeastern U.S. J. Irrigation and Drainage Engineering, ASCE 121(4):277-282.

Thornthwaite, C.W. 1948. An approach toward a rational classification of climate. Geographical Reviw 38(1):55-94

Toksoz, S. and D. Kirkham. 1971. Steady drainage of layered soils: II, Nomographs. J. Irrigation and Drainage Engineering, ASCE 97(IR1):19-37.

Trafford, B.D. and D.W. Rycroft. 1974. The natural soil as trench backfill. Technical Bulletin: 74/9, Ministry of Agriculture, Fisheries and Food, England. 9 p.

USDA. 1984. Soil Survey of Defiance County, Ohio.United States Department of Agriculture-Soil Conservation Service. 246 p.

Van Beers, W.F.J. 1970. The Auger-Hole Method : a field measurement of the hydraulic conductivity of soil below the watertable. ILRI Bulletin 1. Wageningen, Netherlands. 32 p.

Van Genuchten. M.Th., F.J. Leij and S.R. Yates. 1991. The RETC code for quantifying the hydraulic functions of unsaturated soils, version 1.0. EPA Report 600/2-91/065. U.S. Salinity Laboratory, Agricultural Research Service, USDA, Riverside, California. 85 p.

Van Schilfgaarde, J. 1963. Design of tile drainage for falling water tables. J. Irrigation and Drainage Engineering ASCE 89(IR2):1-11.

Vimoke, B.S. and G.S. Taylor. 1962. Simulating water flow in soil with an electric resistance network. Agr. Res. Serv. 41-65, USDA. 51 p.

Vimoke, B.S., T.D. Tyra, T.J. Thiel and G.S. Taylor. 1963. Improvements in construction and use of resistance networks for studying drainage problems. Soil Science Society of American J. 26(2):203-207.

Williams, J.R., A.D. Nicks and J.G. Arnold. 1985. Simulator for water resources in rural basins. J. Hydraulic Engineering ASCE 3(6):970-986.

Workman, S. R. 1999. Personal communication. Department of Biosystems and Agricultural Engineering, University of Kentucky, Lexington, Kentucky.

Workman, S.R. and R.W. Skaggs. 1989. Comparison of two drainage simulation models using field data. Transactions of the ASAE 32(6):1933-1938.

Workman, S.R. and R.W. Skaggs. 1990. PREFLO: A water management model capable of simulating preferential flow. Transactions of the ASAE 33(6):1939-1948.

Workman, S.R. and R.W. Skaggs. 1991. Evaluation of the water management model. PREFLO. Transactions of the ASAE 34(5):2053-2059.

Workman, S.R., R.W. Skaggs, J.E. Parsons and J. Rice (Eds). 1986. DRAINMOD User's Manual. Biological and Agricultural Engineering Department, North Carolina State University, Raleigh, North Carolina. 90 p.

Yu S.C. and K.D. Konyha. 1992. Boundary modelling of steady saturated flow to drain tubes. 305-313. In Proc. of the 6'th International Drainage Symposium. ASAE. 501 p.

Zhang, X.C., M.A. Nearing, L.M. Risse and K.C. McGregor. 1996. Evaluation of WEPP runoff and soil loss predictions using natural runoff plot data. Transactions of the ASAE 39(3):855-863.

APPENDICES

APPENDIX A

Figures 1 (p:923), 2 (p:923), and 3 (p:924), and Table 2 (p:924) from Skaggs et al. (1981)

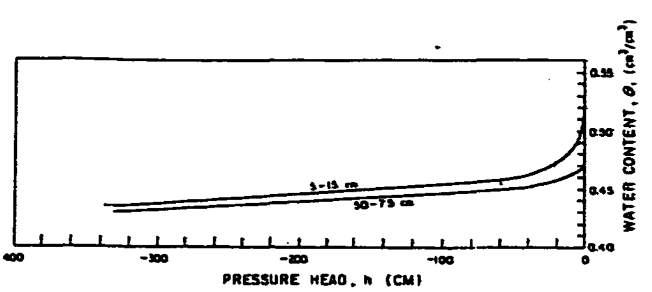

FIG. 1 Soil water characteristics for two depths of the Toledo soil.

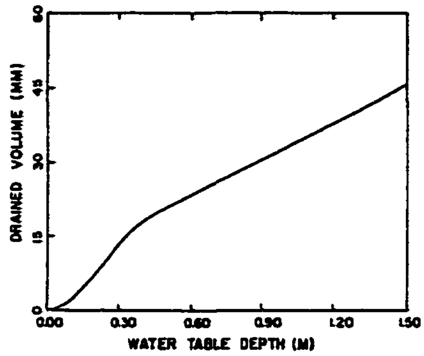

FIG. 2 Drainage volume as a function of water table depth as calculated from the soil water characteristic for Toledo silty clay.

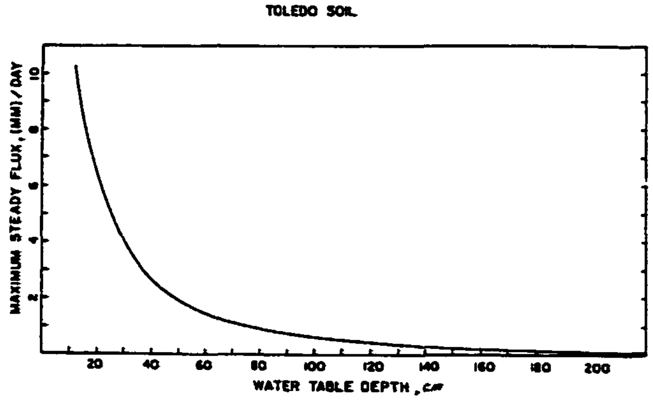

FIG. 3 Maximum steady upward flux calculated from numerical solutions of equation [1] as a function of water table depth.

TABLE 2. PARAMETERS FOR THE GREEN-AMPT EQUATION FOR VARIOUS WATER TABLE DEPTHS AT THE START OF RAINFALL

Water table depth, cm	$A = K_s M S_{av}$, cm^2/h	$B = K_s$, cm/h
0	0	0.4
20	0.55	0.4
50	0.70	0.4
100	0.85	0.4
200	1.90	4.1
500	1.90	4.1

APPENDIX B

Table B1

Midspace Water Table Elevation[+]	Drain Flow	Equivalent Hydraulic Conductivity[*] (cm/day)		
(cm)	(cm/day)	van Schilfgaarde	Hooghoudt	Kirkham[**]
20.4	0.010	0.38	1.52	1.60
45.7	0.025	0.74	1.47	1.85
61.0	0.094	2.34	3.68	5.21
76.2	0.610	13.26	17.35	26.87
91.4	6.838	132.44	149.00	251.59

+: These midspace water table elevations relate to the bottom of the soil layers as abstracted from Schwab et al. (1963).

*: Values calculated with the van Schilfgaarde and Hooghoudt equations using the following parameter values as: Drain spacing = 12.2 m (40 ft), depth to impermeable layer = 75 cm (2.46 ft), drain radius = 5 cm (0.16 ft), equivalent depth = 47.52 cm (1.56 ft), and initial water table elevation = 90 cm (3.0 ft).

**: Figure 1 by Toksoz and Kirkham (1971) (Appendix D) was used. Because of the equations differences between the one used for Figure 1 by Toksoz and Kirkham (1971) and the one given by Hoffman (1963), the calculated hydraulic conductivities from Figure 1 was divided by 3.64 (determined after calculating hydraulic conductivities in Table 7 (Appendix E) by Hoffman (1963) again using Figure 1). Determination of value 3.64 is given in Appendix D.

Table B1. Equivalent saturated hydraulic conductivity values (K_e) of Toledo silty clay as a function of midspace water table elevation above drain. These conductivity values were calculated using the van Schilfgaarde, Hooghoudt, and Kirkham equations (Hoffman, 1963).

APPENDIX C

Table A1 (p:31) from Schwab et al. (1963)

APPENDIX A

Table A1. Physical properties of Toledo Silty Clay. Drainage experimental site, North Central Substation, 1957

Horizon	Depth	Sand	Silt	Clay	pH	Bulk Density	Hydraulic Conductivity[1]	Moisture Retention[1] 60 cm.	Moisture Retention[1] 15 atmos.
	(in.)	(%)	(%)	(%)		(g./cc.)	(in./day)	(% by volume)	
A_p	0-8	3	46	51	5.8	1.22	24.0	41	21
B_{1g}	8-13	3	43	54	6.4	1.39	2.8	42	25
B_{21g}	13-20	4	41	55	6.7	1.43	1.3	46	27
B_{22g}	20-30	3	38	59	7.0	1.45	0.9	46	28
B_{23g}	30-38	2	40	58	7.0	1.48	1.6	44	30
C_{11}	38-50	5	48	47	7.2	1.49	--	43	28
C_{12}	50-64	3	45	52	7.5	1.40	--	--	25
C_2	64-70'	3	44	53	7.5	--	--	--	--

[1] Saturated conductivities and moisture contents at 60 cm. suction were determined from 3-inch diameter soil cores. Each value reported is the average from 6 cores. The 15 atmosphere moisture determinations were made on disturbed soil samples.

APPENDIX D

Figure 1 (p:20) from Toksoz and Kirkham (1971) with an Example K_e (effective saturated hydraulic conductivity) (K_l in Figure 1) calculation.

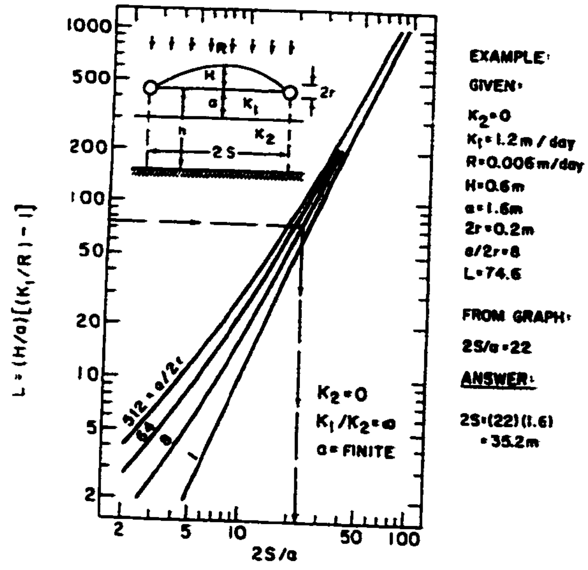

FIG. 1.—DRAIN SPACING NOMOGRAPH FOR $K_2 = 0$

Example: a, H, Q are given in Table 7 (Appendix E) by Hoffman (1963).

a= 0.91 m (3 ft); 2r=0.1 m; a/2r= 9.1; S= 12.2 m; 2S/a= 26.8

L= 105 from Figure 1 for 2S/a and a/2r

Equation on the axis of Y of Figure 1 is:

$$L = (H / a)[(K_t / Q) - 1] \ldots\ldots A1$$

From Table 7 (Appendix E) by Hoffman (1963), for H=0.53 m (1.75 ft), Q = 0.00051 m/day (0.02 in/day). K_t derived form of Equation A1 is:

$$K_t = (\frac{aL}{H} + 1)Q \ldots\ldots A2$$

After substituting the values if the parameters in Equation A2, K_t = 0.0924 m/day (3.64 in/day). Answer for K_t in Table 7 for H = 0.53 m (1.75 ft) by Hoffman (1963) is 1 in/day. To get same value, use a multiplication factor of 1/3.64 in/day.

APPENDIX E

Table 7 (p:67) from Hoffman (1963)

Table 7. Hydraulic Conductivities Calculated from Theoretical Tile Spacing Equations.

Midplane* Water Table Ht. ft.	Tile* Flow in./day	Hydraulic Conductivities**			
		Glover in./day	van Schilfgaarde in./day	Hooghoudt in./day	Kirkham in./day
1.75	0.02	2	0.4	0.7	1
2.00	0.04	3	0.7	1.0	2
2.25	0.08	8	1.4	2.0	3
2.50	0.23	22	3.8	5.0	9
2.75	0.66	71	10.0	12.0	22
2.90	1.32	173	20.0	22.0	43
3.00	2.14	286	32.0	35.0	67

*Midplane water table height and tile flow measurements taken from Figure 37.

**Based on the following field data: tile spacing = 40 ft., depth to impermeable layer = 3.0 ft., tile radius = .20 ft., equivalent depth = 2.6 ft., constant A = .865, and the initial water table height = 3.1 ft.

APPENDIX F

Table 4 (p:14) from Taylor et al. (1970)

TABLE 4.—Soil Hydraulic Conductivity in Inches per Hour of the Toledo Silty Clay as Evaluated by Monoliths in This Study and by Drain Outflow Rates and Midplane Water Table Elevations. The Soil Conservation Service Assigned Permeability Class is Given in the Last Column.

Soil Depth (in.)	Monolith Method	Drain Outflow		SCS Permeability Class
		Hoffmann and Schwab (4)	Taylor, et al. (7)	
0-8	0.55	0.68	0.43*	"Slow" (.063 to 0.20 in. per hr.)
8-20	0.40	0.11		
20-40	0.04	0.02		
40-60	0.02	—	—	

*Equivalent hydraulic conductivity for upper 36 inches of soil.

APPENDIX G

Figure 3 (p:145) from Taylor and Fausey (1982)

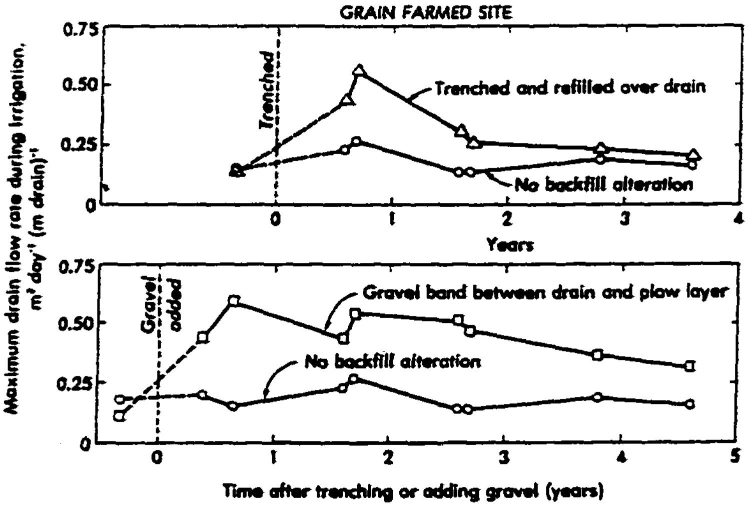

Fig. 3 Effect of Gravel or Trenching and Refilling Directly Over Drains on Flow Rates for Different Times at the Grain Farmed Site. Each Point on the Curve Represents a Flow Measurement Date.

APPENDIX H

Tables H.1, H.2, H.3, and H.4

		Analytical Methods Using Drain Outflow Data						Monolith Method		Core Method		Auger Hole Method		MUUF Soil Database	
		van Schilfgaarde		Hooghoudt		Kirkham									
Year	Replications	Drain flow	Runoff	Drain flow	Runoff	Drain flow	Runoff	Drain flow	Runoff	Drain flow	Runoff	Drain flow	Runoff	Drain flow	Runoff
1962	1	0.0311	0.0084	0.0306	0.0086	0.0506	0.0099	0.0458	0.0139	0.0466	0.0128	0.0317	0.0084	0.0448	0.0144
	2	0.0202	0.0180	0.0197	0.0174	0.0310	0.0107	0.0285	0.0197	0.0305	0.0188	0.0231	0.0141	0.0342	0.0196
	3	0.0821	0.0161	0.0822	0.0151	0.0841	0.0045	0.0624	0.0182	0.0643	0.0145	0.0873	0.0128	0.0614	0.0128
	4	0.0576	0.0067	0.0585	0.0075	0.0584	0.0172	0.0426	0.0196	0.0443	0.0208	0.0642	0.0096	0.0387	0.0201
	Average	0.048	0.012	0.048	0.012	0.056	0.010	0.045	0.017	0.046	0.016	0.052	0.011	0.045	0.016
1963	1	0.0570	0.0023	0.0566	0.0016	0.0517	0.0019	0.0612	0.0070	0.0601	0.0027	0.0508	0.0028	0.0595	0.0040
	2	0.0274	0.0079	0.0281	0.0080	0.0292	0.0084	0.0391	0.0136	0.0399	0.0145	0.0263	0.0060	0.0415	0.0137
	3	0.0365	0.0073	0.0377	0.0067	0.0386	0.0067	0.0519	0.0151	0.0522	0.0138	0.0359	0.0046	0.0540	0.0130
	4	0.0538	0.0091	0.0528	0.0089	0.0570	0.0094	0.0675	0.0170	0.0653	0.0178	0.0551	0.0069	0.0663	0.0181
	Average	0.044	0.007	0.044	0.006	0.044	0.007	0.055	0.013	0.054	0.012	0.042	0.005	0.055	0.012
1964	1	0.0700	0.0121	0.0695	0.0119	0.0801	0.0099	0.0766	0.0277	0.0772	0.0254	0.0798	0.0135	0.0798	0.0266
	2	0.0542	0.0129	0.0537	0.0127	0.0623	0.0108	0.0634	0.0284	0.0637	0.0266	0.0622	0.0143	0.0675	0.0273
	3	0.0664	0.0143	0.0644	0.0138	0.0704	0.0128	0.0787	0.0356	0.0764	0.0323	0.0753	0.0149	0.0781	0.0320
	4	0.0839	0.0019	0.0811	0.0025	0.0887	0.0038	0.0946	0.0244	0.0920	0.0210	0.0934	0.0043	0.0932	0.0204
	Average	0.069	0.010	0.067	0.010	0.075	0.009	0.078	0.029	0.077	0.026	0.078	0.012	0.080	0.027
1967	1	0.0329	0.0243	0.0347	0.0254	0.0409	0.0270	0.0474	0.0302	0.0479	0.0303	0.0487	0.0269	0.0547	0.0304
	2	0.0327	0.0303	0.0340	0.0302	0.0385	0.0297	0.0448	0.0362	0.0466	0.0368	0.0474	0.0296	0.0533	0.0369
	3	0.0431	0.0284	0.0449	0.0297	0.0502	0.0319	0.0475	0.0228	0.0498	0.0213	0.0578	0.0326	0.0556	0.0200
	4	0.0473	0.0247	0.0494	0.0260	0.0515	0.0282	0.0491	0.0217	0.0511	0.0203	0.0566	0.0290	0.0578	0.0190
	Average	0.039	0.027	0.041	0.028	0.045	0.029	0.047	0.028	0.049	0.027	0.053	0.029	0.055	0.027

Table H.1. Average deviation (cm) between observed daily and predicted drain flow and runoff for seven different hydraulic conductivity value estimation methods. The observed values were obtained from the drainage experiment of OARDC North Central Branch, near Sandusky, Ohio (Schwab et al., 1963; 1975; and 1985). (continued)

(Table H.1 is continued)

1968	1	0,0319	0,0267	0.0343	0.0280	0.0342	0.0272	0.0415	0.0212	0.0422	0,0223	0,0398	0,0257	0,0464	0,0247
	2	0,0327	0,0225	0.0339	0.0223	0.0323	0.0204	0.0414	0.0218	0.0424	0,0199	0.0387	0.0373	0.0583	0,0363
	3	0,0339	0.0331	0.0351	0.0330	0.0346	0.0310	0.0445	0,0263	0.0461	0.0250	0,0353	0,0222	0,0456	0,0206
	4	0,0363	0,0383	0.0384	0.0396	0.0398	0.0388	0.0540	0.0328	0.0480	0,0337	0.0365	0.0328	0.0488	0,0248
	Average	0,034	0,030	0.035	0.031	0,035	0,029	0,045	0,025	0.045	0,025	0.038	0.029	0.050	0.027
1969	1	0,0474	0,0219	0.0473	0,0208	0,0512	0.0204	0.1119	0,0785	0.1128	0.0727	0.0607	0.0220	0,1208	0.0708
	2	0,0461	0.0207	0,0469	0,0194	0.0492	0.0186	0.0971	0.0767	0.0985	0.0709	0,0560	0,0202	0.1073	0,0690
	3	0,0429	0.0293	0,0442	0,0296	0.0488	0.0313	0.0812	0.0674	0.0815	0.0621	0,0542	0,0326	0,0906	0.0596
	4	0,0367	0.0566	0,0399	0.0577	0.0479	0.0596	0.0852	0.0780	0,0821	0.0727	0.0599	0.0609	0.0919	0.0716
	Average	0,043	0,032	0.045	0.032	0.049	0.032	0.094	0.075	0.094	0.070	0.058	0.034	0.103	0.068
1970	1	0,0557	0,0260	0,0586	0,0275	0.0705	0.0302	0.0974	0.0305	0.0986	0,0298	0.0590	0,0317	0.1081	0.0300
	2	0,0425	0,0297	0.0438	0,0309	0.0539	0.0340	0.0749	0.0404	0.0759	0,0397	0.0474	0.0350	0.0857	0.0409
	3	0,0623	0,0547	0,0654	0,0551	0.0758	0,0631	0.0879	0.0655	0.0901	0.0636	0.0721	0.0544	0.0980	0.0497
	4	0,0584	0.0786	0,0599	0,0790	0,0662	0.0870	0.0803	0.0823	0.0827	0.0809	0.0678	0.0783	0.0916	0.0670
	Average	0,055	0,047	0.057	0.048	0.067	0.054	0.085	0.055	0.087	0.053	0.062	0.050	0.096	0.047
1971	1	0,0391	0,0133	0,0413	0,0122	0.0423	0.0107	0.0496	0.0208	0.0497	0.0230	0.0429	0.0093	0.0523	0.0225
	2	0,0169	0,0205	0.0182	0.0194	0.0193	0.0180	0.0379	0.0275	0.0384	0.0288	0.0227	0.0166	0.0418	0.0292
	3	0.0191	0,0217	0,0211	0.0230	0,0223	0.0246	0.0297	0.0096	0.0293	0.0101	0.0226	0.0262	0.0331	0.0109
	4	0,0210	0,0251	0,0226	0.0263	0,0238	0.0280	0.0273	0.0129	0.0270	0.0119	0.0238	0.0295	0.0307	0.0133
	Average	0,024	0.020	0,026	0.020	0.027	0.020	0.036	0.018	0.036	0.018	0.028	0.020	0.039	0.019

		Analytical Methods Using Drain Outflow Data													
		van Schilfgaarde		Hooghoudt		Kirkham		Monolith Method		Core Method		Auger Hole Method		MUUF Soil Database	
Year	Replications	Drain flow	Runoff	Drain flow	Runoff	Drain flow	Runoff	Drain flow	Runoff	Drain flow	Runoff	Drain flow	Runoff	Drain Flow	Runoff
1962	1	1.941	0.078	1.779	0.136	3.096	0.997	3.871	0.512	3.465	0.577	1.435	0.213	3.168	0.411
	2	0.638	1.104	0.478	1.046	0.859	0.064	2.343	1.270	1.803	0.968	0.763	0.742	2.086	0.940
	3	3.701	1.504	3.500	1.405	3.811	0.242	5.463	1.687	4.918	1.304	3.039	1.183	5.064	1.135
	4	1.773	0.699	1.606	0.778	2.058	1.818	2.984	0.962	2.622	1.299	1.218	0.969	2.678	1.356
	Average	2.013	0.846	1.841	0.841	2.456	0.701	3.665	1.029	3.202	0.969	1.614	0.777	3.249	0.883
1963	1	6.454	0.090	6.380	0.159	5.850	0.202	6.656	0.403	6.438	0.053	5.787	0.292	6.459	0.117
	2	2.937	0.403	2.831	0.530	2.634	0.664	3.796	0.342	3.525	0.079	2.289	0.634	3.519	0.142
	3	4.335	0.063	4.276	0.130	4.207	0.130	5.472	0.940	5.149	0.704	3.626	0.338	5.231	0.626
	4	6.567	0.572	6.422	0.441	6.354	0.450	7.951	1.718	7.646	1.443	5.901	0.355	7.677	1.336
	Average	5.073	0.282	4.977	0.315	4.761	0.361	5.969	0.851	5.689	0.570	4.401	0.405	5.721	0.555
1964	1	3.722	1.001	3.648	1.062	3.459	1.029	5.884	1.981	5.020	1.119	3.086	1.094	5.185	1.477
	2	1.732	1.097	1.633	1.159	1.443	1.125	3.309	1.884	2.862	1.026	1.201	1.191	2.908	1.381
	3	2.926	0.332	2.781	0.463	2.516	0.648	5.092	2.906	4.515	2.241	2.285	0.634	4.641	2.491
	4	6.519	0.087	6.398	0.237	6.135	0.422	9.281	3.132	8.426	2.467	5.739	0.408	8.741	2.717
	Average	3.725	0.626	3.614	0.730	3.500	0.405	5.581	2.041	5.152	1.679	3.078	0.832	5.123	1.617
1967	1	2.429	1.331	2.661	1.548	3.026	1.822	1.449	2.482	1.054	2.159	3.295	1.828	1.016	1.933
	2	3.098	1.272	3.330	1.446	3.694	1.623	0.936	2.915	0.632	2.591	3.962	1.629	0.604	2.366
	3	4.122	2.744	4.406	3.053	4.862	3.526	1.101	0.980	1.067	0.655	5.021	3.556	1.342	0.485
	4	5.621	1.943	5.905	2.252	6.360	2.725	2.099	1.795	2.565	1.471	6.519	2.749	2.841	1.243
	Average	3.817	1.822	4.075	2.075	4.485	2.424	1.396	2.043	1.329	1.719	4.699	2.440	1.451	1.507

Table H.2. Average deviation (cm) between cumulative observed and predicted drain flow and runoff for seven different hydraulic conductivity value estimation methods. The observed values were obtained from the drainage experiment of OARDC North Central Branch, near Sandusky, Ohio (Schwab et al., 1963; 1975; and 1985). (continued)

(Table H.2 is continued)

1968	1	0.693	2,492	0,929	2,659	1.098	2,748	1,329	0,850	1,120	0,979	1.701	3,160	0,955	1,131
	2	0.433	1,320	0,533	1,434	0,837	1,632	2,281	1,148	2,042	0,929	1,154	1,709	1,983	0,870
	3	0,647	2,540	0,506	2,654	0,440	2,852	2,650	0,620	2,412	0,743	0,755	2,930	2,353	0,775
	4	1,289	3,876	1,094	4,043	0,969	4,131	3,176	2,111	2,968	2,313	0,574	4,544	2,803	2,515
Average		0,765	2,557	0,765	2,697	0,836	2,841	2,359	1,182	2,135	1,242	1,046	3,086	2,023	1,323
1969	1	1,577	2,498	1,912	2,144	2,474	1,761	6,563	10,264	5,823	9,502	2,714	1,794	5,710	9,278
	2	4,301	2,366	4,636	2,012	5,198	1,629	4,018	10,131	3,322	9,369	3,185	9,146	5,437	1,662
	3	5,732	0,375	6,092	0,076	6,682	0,441	2,011	7,512	1,345	6,750	6,884	0,411	1,207	6,538
	4	1,941	3,035	2,301	3,400	2,890	3,800	5,481	4,131	4,742	3,369	3,093	3,731	4,639	3,157
Average		3,388	2,068	3,735	1,908	4,311	1,908	4,518	8,009	3,808	7,247	4,532	1,899	3,685	7,030
1970	1	1,319	2,783	1,382	2,945	1,865	3,205	3,396	0,847	3,065	0,691	2,278	3,382	2,932	0,474
	2	3,844	3,283	4,031	3,446	4,514	3,705	1,287	0,465	1,097	0,508	4,929	3,882	1,130	0,505
	3	3,120	5,851	3,360	6,065	3,797	6,280	2,672	2,512	2,359	2,694	4,137	6,375	2,238	3,136
	4	2,318	8,431	2,558	8,645	2,995	8,860	2,001	5,092	1,655	5,274	3,335	8,955	1,528	5,716
Average		2,650	5,087	2,833	5,275	3,293	5,512	2,339	2,229	2,044	2,292	3,670	5,648	1,957	2,458
1971	1	1,265	0,414	1,131	0,528	0,906	0,681	3,035	1,102	3,204	1,521	0,660	0,822	3,154	1,163
	2	0,354	0,993	0,237	1,107	0,244	1,260	2,040	0,887	2,237	1,201	0,517	1,401	2,162	0,951
	3	0,426	2,357	0,579	2,491	0,846	2,662	1,489	0,815	1,618	0,378	1,140	2,817	1,580	0,783
	4	1,207	2,699	1,358	2,832	1,632	3,004	0,785	1,157	0,973	0,719	1,935	3,158	0,897	1,125
Average		0,813	1,616	0,826	1,739	0,907	1,902	1,837	0,990	2,008	0,955	1,063	2,049	1,948	1,005

			Analytical Methods Using Drain Outflow Data													
		Measured	van Schilfgaarde		Hooghoudt		Kirkham		Monolith Method		Core Method		Auger Hole Method		MUUF Soil Database	
Year	Replications	Drain Flow	Drain Flow	Difference	Drain Flow	Difference	Drain Flow	Difference	Drain Flow	Difference	Drain Flow	Difference	Drain Flow	Difference	Drain Flow	Difference
1962	1	9.10	6.26	-2.84	6.53	-2.57	5.54	-3.56	3.39	-5.71	4.28	-4.82	7.12	-1.98	4.78	-4.32
	2	6.58	6.14	-0.44	6.40	-0.18	6.58	0.00	3.20	-3.38	4.32	-2.26	7.40	+0.82	4.18	-2.40
	3	11.98	6.97	-5.01	7.30	-4.68	7.60	-4.38	3.98	-8.00	4.97	-7.01	8.11	-3.87	5.21	-6.77
	4	7.92	4.86	-3.06	5.14	-2.78	4.97	-2.95	2.86	-5.06	3.91	-4.01	5.85	-2.07	3.86	-4.06
	Average	8.89	6.06	-2.84	6.34	-2.55	6.17	-2.72	3.36	-5.54	4.37	-4.52	7.12	-1.77	4.51	-4.39
1963	1	13.09	2.65	-10.44	2.78	-10.31	3.67	-9.42	2.13	-10.96	2.40	-10.69	2.45	-9.31	3.78	-10.64
	2	8.87	4.07	-4.80	4.25	-4.62	4.59	-4.28	2.46	-6.41	2.91	-5.96	2.95	-3.70	5.17	-5.92
	3	11.75	5.34	-6.41	5.44	-6.31	5.55	-6.20	3.35	-8.40	3.80	-7.95	3.75	-5.27	6.48	-8.00
	4	15.43	5.60	-9.83	5.84	-9.59	5.94	-9.49	3.15	-12.28	3.62	-11.82	3.65	-8.76	6.67	-11.78
	Average	12.28	4.41	-7.87	4.58	-7.71	4.94	-7.35	2.77	-9.51	3.18	-9.10	3.20	-6.76	5.52	-9.08
1964	1	19.66	14.18*	-5.48	14.31	-5.35	14.68	-4.98	9.92	-9.74	11.40	-8.26	15.43	-4.23	11.07	-8.59
	2	15.55	14.18*	-1.37	14.31	-1.24	14.68	-0.87	9.92	-5.63	11.40	-4.15	15.43	-0.12	11.07	-4.48
	3	19.75	15.40	-4.35	15.63	-4.12	16.14	-3.61	10.51	-9.24	11.79	-7.96	16.84	-2.91	11.34	-8.41
	4	25.88	15.40	-10.48	15.63	-10.25	16.14	-9.74	10.51	-15.37	11.79	-14.09	16.84	-9.04	11.34	-14.54
	Average	20.21	14.79	-5.42	14.97	-5.24	15.41	-4.80	10.21	-9.99	11.59	-8.61	16.13	-4.07	11.20	-9.00
1967	1	11.45	14.06	+2.61	14.41	+2.96	14.93	+3.48	9.41	-2.04	10.15	-1.30	15.39	+3.94	10.39	-1.06
	2	10.48	14.06	+3.58	14.41	+3.93	14.93	+4.45	9.41	-1.07	10.15	-0.33	15.39	+4.91	10.39	-0.09
	3	9.75	14.18	+4.43	14.62	+4.87	15.30	+5.55	9.20	-0.55	9.86	+0.11	15.58	+5.83	10.18	+0.43
	4	7.38	14.18	+6.80	14.62	+7.24	15.30	+7.92	9.20	+1.82	9.86	+2.48	15.58	+8.20	10.18	+2.80
	Average	9.76	14.12	+4.35	14.51	+4.75	15.11	+5.35	9.30	-0.46	10.00	+0.24	15.48	+5.72	10.28	+0.52

*; They are from same DRAINMOD run because the model was run one times for two replications starting in 1964.

Table H.3. Measured (at the drainage experiment station of OARDC North Central Branch, near Sandusky, Ohio) and predicted drain flows (cm) and the differences between them for the seven hydraulic conductivity methods evaluated. (continued)

(Table H.3 is continued)

1968	1	8.40	8.94	+0.54	9.28	+0.88	9.52	+1.12	6.32	-2.08	6.61	-1.79	10.40	+2.00	6.90	-1.50
	2	9.25	9.06	-0.19	9.43	+0.18	9.85	+0.60	5.66	-3.59	6.06	-3.19	10.27	+1.02	6.16	-3.09
	3	9.85	9.06	-0.79	9.43	-0.42	9.85	0.00	5.66	-4.19	6.06	-3.79	10.27	+0.42	6.16	-3.69
	4	11.11	8.94	-2.17	9.28	-1.83	9.52	-1.59	6.32	-4.79	6.61	-4.50	10.40	-0.72	6.90	-4.21
	Average	9.65	9.00	-0.65	9.35	-0.31	9.68	+0.03	5.99	-3.66	6.33	-3.32	10.33	+0.68	6.53	-3.12
1969	1	22.90	23.49	+0.59	24.05	+1.15	24.85	+1.95	12.66	-10.24	13.78	-9.12	25.23	+2.33	14.04	-8.86
	2	18.93	23.49	+4.56	24.05	+5.12	24.85	+5.92	12.66	-6.27	13.78	-5.15	25.23	+6.30	14.04	-4.89
	3	15.38	22.18	+6.80	22.79	+7.41	23.64	+8.26	12.43	-2.95	13.51	-1.87	23.96	+8.58	13.77	-1.61
	4	19.98	22.18	+2.20	22.79	+2.81	23.64	+3.66	12.43	-7.55	13.51	-6.47	23.96	+3.98	13.77	-6.21
	Average	19.30	22.83	+3.54	23.42	+4.12	24.24	+4.95	12.54	-6.75	13.64	-5.65	24.59	+5.30	13.90	-5.39
1970	1	15.05	14.78	-0.27	15.09	+0.04	15.81	+0.76	9.39	-5.66	10.06	-4.99	16.44	+1.39	10.44	-4.61
	2	10.54	14.78	+4.24	15.09	+4.55	15.81	+5.27	9.39	-1.15	10.06	-0.48	16.44	+5.90	10.44	-0.10
	3	12.27	14.35	+2.08	14.76	+2.49	15.40	+3.13	9.28	-2.99	10.00	-2.27	15.90	+3.63	10.38	-1.89
	4	12.15	14.35	+2.20	14.76	+2.61	15.40	+3.25	9.28	-2.87	10.00	-2.15	15.90	+3.75	10.38	-1.77
	Average	12.50	14.56	+2.06	14.92	+2.42	15.60	+3.10	9.33	-3.17	10.03	-2.47	16.17	+3.67	10.41	-2.09
1971	1	8.22	6.28	-1.94	6.51	-1.71	6.89	-1.33	3.29	-4.93	3.13	-5.09	7.32	-0.90	3.16	-5.06
	2	6.72	6.28	-0.44	6.51	-0.21	6.89	+0.17	3.29	-3.43	3.13	-3.59	7.32	+0.60	3.16	-3.56
	3	5.77	6.35	+0.58	6.61	+0.84	7.05	+1.28	3.34	-2.43	3.22	-2.55	7.53	+1.76	3.24	-2.53
	4	4.68	6.35	+1.67	6.61	+1.93	7.05	+2.37	3.34	-1.34	3.22	-1.46	7.53	+2.85	3.24	-1.44
	Average	6.35	6.31	-0.03	6.56	+0.21	6.97	+0.62	3.31	-3.03	3.17	-3.17	7.42	+1.08	3.20	-3.15
	Average Total	98.94	92.08	-6.86	94.65	-4.31	98.12	-0.82	56.81	-42.20	62.31	-36.60	100.44	+3.85	65.55	-35.70

			Analytical Methods Using Drain Outflow Data													
		Measured	van Schilfgaarde		Hooghoudt		Kirkham		Monolith Method		Core Method		Auger Hole Method		MUUF Soil Database	
Year	Replications	Runoff	Runoff	Difference	Runoff	Difference	Runoff	Difference	Runoff	Difference	Runoff	Difference	Runoff	Difference	Runoff	Difference
1962	1	1,81	1.79	-0,02	1,65	-0,16	0.00	-1,81	1.09	-0.72	0,90	-0,91	1,48	-0,33	1,19	-0,62
	2	1,62	3,59	+1,97	3,48	+1,86	1,64	-0,02	4,16	+2,54	3,52	+1,90	2,88	+1,26	3,44	+1,82
	3	1,02	3,55	+2,53	3,37	+2,35	1,43	+0,41	4,19	+3,17	3,52	+2,50	2,95	+1,93	3,21	+2,19
	4	4,56	3,34	-1,22	3,19	-1,37	1,42	-3,14	3,13	-1,43	2,52	-2,04	2,80	-1,76	2,40	-2,16
	Average	2,25	3,07	+0,81	2,92	+0,67	1,12	-1,14	3,14	+0,89	2,61	+0,36	2,53	+0,27	2,56	+0,31
1963	1	0,66	0,53	-0,13	0,40	-0,26	0,32	-0,34	1,38	+0,72	0,60	-0,06	0,15	-0,51	0,84	+0,18
	2	2,36	1,70	-0,66	1,48	-0,88	1,25	-1,11	2,91	+0,55	2,37	+0,01	1,27	-1,09	2,23	-0,13
	3	1,92	1,90	-0,02	1,78	-0,14	1,78	-0,14	3,53	+1,61	3,08	+1,16	1,41	-0,51	2,94	+1,02
	4	1,62	2,60	+0,98	2,35	+0,73	2,36	+0,74	4,70	+3,08	4,16	+2,54	2,21	+0,59	3,95	+2,33
	Average	1,64	1,68	+0,04	1,50	-0,14	1,43	-0,21	3,13	+1,49	2,55	+0,91	1,26	-0,38	2,49	+0,85
1964	1	3,80	2,22*	-1,58	2,10	-1,70	2,16	-1,64	6,60	+2,80	5,37	+1,57	2,03	-1,77	5,89	+2,09
	2	3,94	2,22*	-1,72	2,10	-1,84	2,16	-1,78	6,60	+2,66	5,37	+1,43	2,03	-1,91	5,89	+1,95
	3	2,73	2,50	-0,25	2,20	-0,53	1,84	-0,89	7,48	+4,75	6,46	+3,73	1,86	-0,87	6,77	+4,04
	4	2,65	2,50	-0,15	2,20	-0,45	1,84	-0,81	7,48	+4,83	6,46	+3,81	1,86	-0,79	6,77	+4,12
	Average	3,28	2,36	-0,92	2,15	-1,13	2,00	-1,28	7,04	+3,76	5,91	+2,63	1,94	-1,33	6,33	+3,05
1967	1	5,28	3,15	-2,13	2,73	-2,55	2,25	-3,03	7,94	+2,66	7,46	+2,18	2,25	-3,03	7,15	+1,87
	2	4,81	3,15	-1,66	2,73	-2,08	2,25	-2,56	7,94	+3,13	7,46	+2,68	2,25	-2,56	7,15	+2,34
	3	8,76	4.30	-4,46	3.85	-4,91	3,17	-5,59	9,47	+0,71	8.99	+0,23	3,11	-5,65	8.67	-0,09
	4	7,43	4,30	-3,13	3,85	-3,58	3,17	-4,26	9,47	+2,04	8,99	+1,56	3,11	-4,32	8,67	+1,24
	Average	6,57	3,72	-2,84	3,29	-3,28	2,71	-3,86	8,70	+2,13	8,22	+1,66	2,68	-3,89	7,91	+1,34

*: They are from same DRAINMOD run since the model was run one times for two replications starting in 1964.

Table H.4. Measured and predicted Runoff flows (cm) and the differences between them for the seven hydraulic conductivity methods evaluated. The measured values were obtained from the drainage experiment of OARDC North Central Branch, near Sandusky, Ohio (Schwab et al., 1963; 1975; and 1985). (continued)

(Table H.4 is continued)

1968	1	7.55	3.78	-3.78	3.55	-4.00	3.43	-4.12	6.22	-1.33	5.95	-1.60	2.84	-4.71	5.67	-1.85
	2	6.25	4.16	-2.09	4.00	-2.25	3.72	-2.53	7.61	+1.36	7.31	+1.06	3.61	-2.64	7.23	+0.98
	3	8.20	4.16	-4.04	4.00	-4.20	3.72	-4.48	7.61	-0.59	7.31	-0.89	3.61	-4.59	7.23	-0.97
	4	9.67	3.78	-5.89	3.55	-6.12	3.43	-6.24	6.22	-3.45	5.95	-3.72	2.84	-6.83	5.67	-4.00
	Average	7.92	3.97	-3.95	3.77	-4.14	3.57	-4.34	6.91	-1.00	6.63	-1.29	3.22	-4.69	6.45	-1.47
1969	1	22.07	25.78	+3.71	25.26	+3.19	24.69	+2.62	36.43	+14.36	35.38	+13.31	24.63	+2.56	35.02	+12.95
	2	22.40	25.78	+3.38	25.26	+2.86	24.69	+2.29	36.43	+14.03	35.38	+12.98	24.63	+2.23	35.02	+12.62
	3	26.46	26.94	+0.48	26.39	-0.07	25.78	-0.68	36.54	+10.08	35.49	+9.03	25.78	-0.68	35.15	+8.69
	4	31.65	26.94	-4.71	26.39	-5.26	25.78	-5.87	36.54	+4.89	35.49	+3.84	25.78	-5.87	35.15	+3.50
	Average	25.64	26.36	+0.71	25.82	+0.18	25.23	-0.41	36.48	+10.84	35.43	+9.79	25.20	-0.44	35.08	+9.44
1970	1	9.82	5.05	-4.77	4.78	-5.04	4.34	-5.48	10.41	+0.59	10.12	+0.30	4.02	-5.80	9.61	-0.21
	2	10.43	5.05	-5.38	4.78	-5.65	4.34	-6.09	10.41	-0.02	10.12	-0.31	4.02	-6.41	9.61	-0.82
	3	14.61	5.78	-8.83	5.42	-9.19	5.06	-9.55	10.82	-3.79	10.51	-4.10	4.89	-9.72	9.98	-4.63
	4	18.98	5.78	-13.20	5.42	-13.56	5.06	-13.92	10.82	-8.16	10.51	-8.47	4.89	-14.09	9.98	-9.00
	Average	13.46	5.41	-8.04	5.10	-8.36	4.70	-8.76	10.61	-2.84	10.31	-3.14	4.45	-9.00	9.79	-3.66
1971	1	3.26	2.81	-0.48	2.61	-0.65	2.34	-0.92	5.32	+2.06	6.07	+2.80	2.09	-1.17	5.42	+2.16
	2	3.93	2.81	-1.12	2.61	-1.32	2.34	-1.59	5.32	+1.39	6.07	+2.14	2.09	-1.84	5.42	+1.49
	3	6.60	2.96	-3.64	2.73	-3.87	2.43	-4.17	5.57	-1.03	6.27	-0.33	2.15	-4.45	5.65	-0.95
	4	7.21	2.96	-4.25	2.73	-4.48	2.43	-4.78	5.57	-1.64	6.27	-0.94	2.15	-5.06	5.65	-1.56
	Average	5.25	2.88	-2.36	2.67	-2.58	2.38	-2.86	5.44	+0.19	6.17	+0.92	2.12	-3.13	5.53	+0.28
Average Total		66.01	49.45	-16.55	47.22	-18.78	43.14	-22.86	81.45	+15.46	77.83	+11.84	43.40	-22.59	76.14	+10.14

APPENDIX, I

Figure 2 (p:169) from Salem and Skaggs (1998)

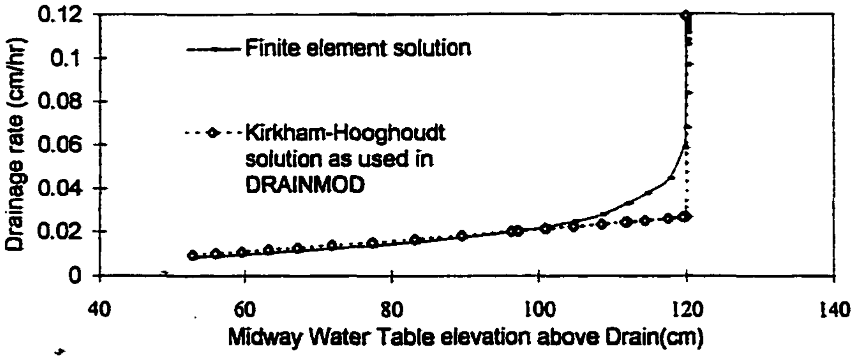

Figure 2 Drain flow rate as a function of midpoint water table elevation for both finite element solution and the approximate approach. Drain spacing=40 m, drain depth=1.2 m, depth to impermeable layer=1.2 m, and effective radius = 5 cm.

APPENDIX J

Figure 4 (p:7) from Schwab et al. (1963)

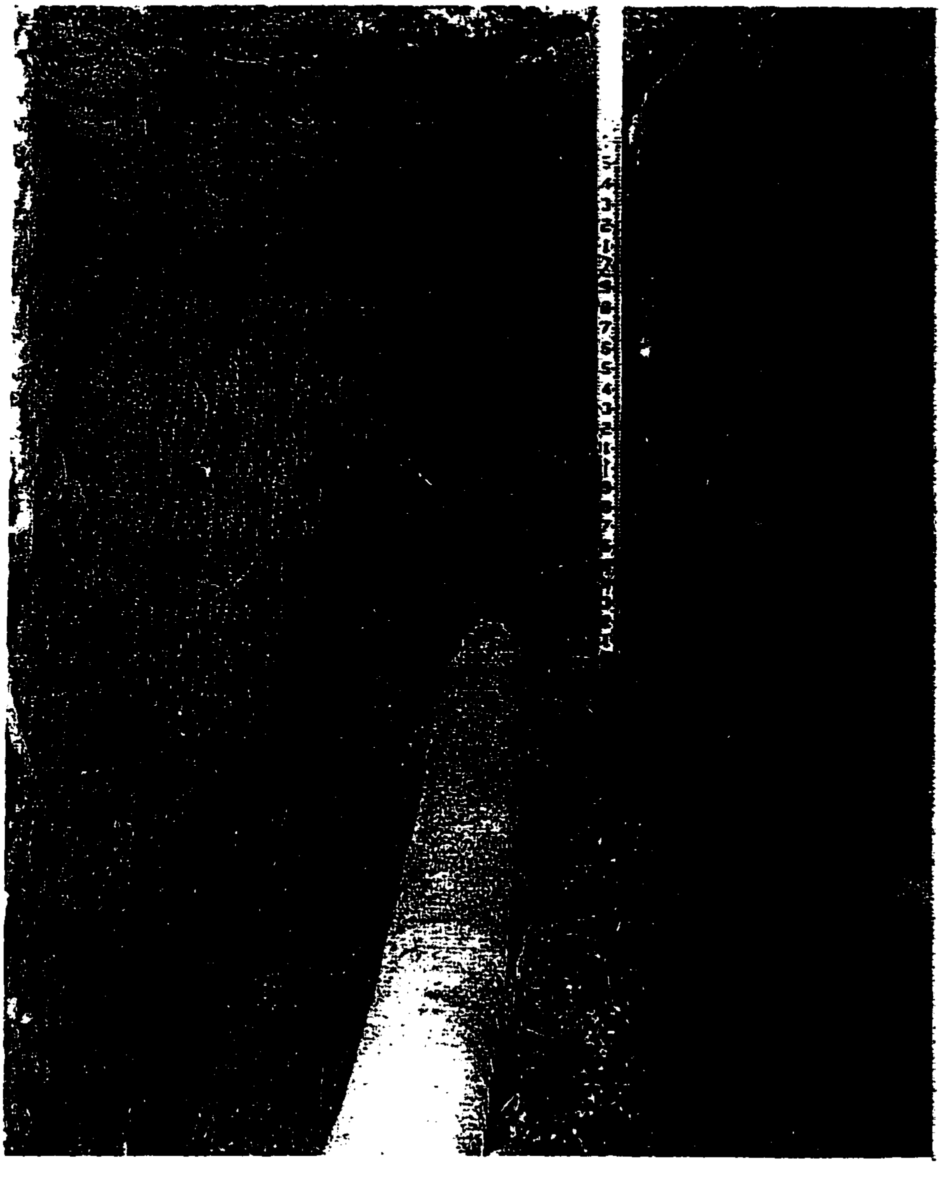

Fig. 4.—Binding the tile with topsoil.

Appendix K

Figures 6.1.1 and 6.1.2 (p:6.1 and 6.2, respectively) from Savabi et al. (1995)

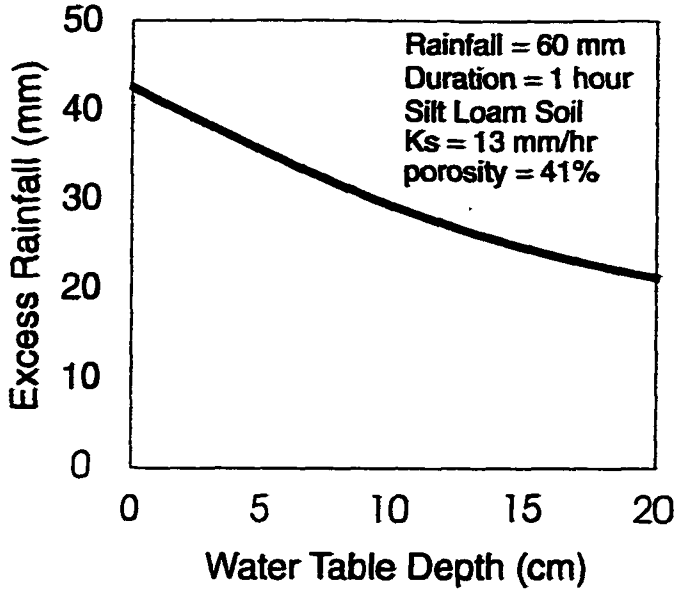

Figure 6.1.1. Sensitivity of the WEPP runoff calculations to water table depth.

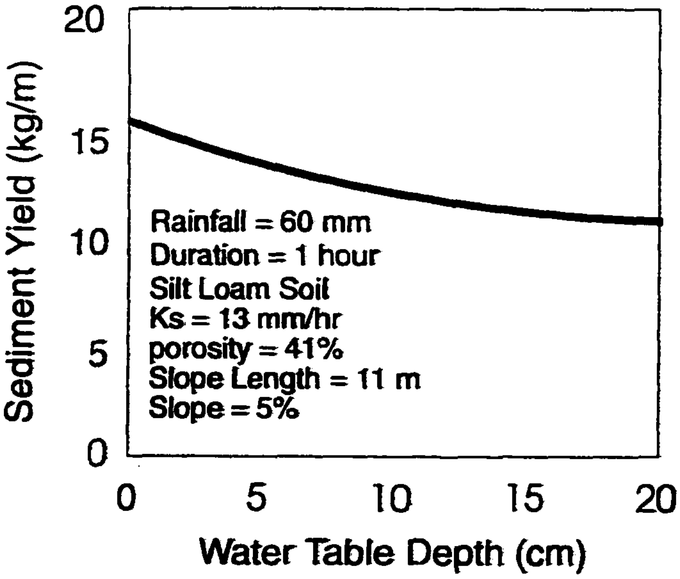

Figure 6.1.2. Sensitivity of the WEPP sediment yield calculations to water table depth.

Appendix L

Tables L.1 and L.2

Line 1: version control number (95.7)-real(datver)

Line 2: user comment line-character*80(solcom)

Line 3: a) number of overland flow elements (OFE's) or channels-integer (ntemp)

- b) flag to use internal hydraulic conductivity adjustments-integer(ksflag)
  - 0-do not use adjustments (conductivity will be held constant)
  - 1-use internal adjustments
- *c) flag to use user lateral saturated hydraulic conductivity values for per soil layer-integer(lsflag)*
  - *0-do not use (WEPP predicted values will be used)*
  - *1-use*
- *d) flag to simulate vertical seepage from bottom of soil profile-integer(vsflag)*
  - *0-do not simulate vertical seepage (assume no vertical seepage)*
  - *1-simulate vertical seepage*
- *e) flag to use user drained volume versus water table depth data-integer(dvflag)*
  - *0-do not use (WEPP-WTM will predict these values)*
  - *1-use*
- *f) flag to use user constant depressional storage depth value-integer(dsflag)*
  - *0-use*
  - *1-do not use (WEPP predicted value will be used)*
- *g) flag to use user PET data-integer(peflag)*
  - *0-use*
  - *1-do not use (WEPP predicted values will be used)*
- *h) flag to use user upward flux versus water table depth data-integer(upflag)*
  - *0-use*
  - *1-do not use (WEPP-WTM will predicted values will be used)*
- *i) flag to use user soil water retention data-integer(flswc)*
  - *0-use*
  - *1-do not use (WEPP predicted values will be used)*

+: lines written in italic are modifications to WEPP for WEPP-WTM.

#: the first pressure value is assigned a value of 0 (saturated water content); the last pressure is assigned a value of −15000 (wilting point).

Table L.1. WEPP-WTM soil input file descriptions[+]. (continued)

(Table L.1. continued)

Lines 4&5 are repeated for the number of OFE's or channels on Line 3a.

Line 4: a) soil name for current OFE or channel-character (slid)

b) soil texture for current OFE or channel-character (texid)

c) number of soil layers for current OFE or channel-integer (nsl)

d) albedo of the bare dry surface soil on the current OFE or channel-real (salb)

e) initial saturation level of the soil profile porosity (m/m)-real (sat)

f) baseline interrill erodibility parameter (kg*s/m^4)-real (ki)

g) baseline rill erodibility parameter (s/m)-real (kr)

h) baseline critical shear parameter (N/m^2)-real (shcrit)

i) effective hydraulic conductivity of surface soil (mm/h)-real (avke)

*Line 5: User comment line–character*80, (solcom2)*

Drained volume versus water table depth data (read when dvflag=1)

Line 6: Number of drained volume versus water table depth point couples-integer (nudvwdp)

Line 7: (repeated for the number of drained volume versus water table depth point couples)

a) water table depth (cm)-integer (watade)

b) drained volume (cm)-real (dravolp)

*Line 8: User comment line-character*80, (solcom3)*

Depressional storage depth data (read when dsflag=0)

Line 9: Depressional storage depth (m)-real (dpress1)

Upward flux data (read when upflag=1)

Line 10:Number of upward flux versus water table depth point couples-integer (nuupwt)

Line 11:(repeated for the number of upward flux versus water table depth point couples)

a) water table depth (cm)-integer (watade2)

b) upward flux (cm/hr)-real (upfl)

*Line 12: User comment line-character*80, (solcom4)*

Line 13: (repeated for the number of soil layers indicated on line 4c.)

a) depth from soil surface to bottom of soil layer (mm)-real (solthk)

b) percentage of sand in the layer (%)-real (sand)

c) percentage of clay in the layer (%)-real (clay)

d) percentage of organic matter (volume) in the layer (%)-real (orgmat)

(continued)

(Table L.1. continued)

e) cation exchange capacity in the layer (meq/100 g of soil)-real (cec)

f) percentage of rock fragments by volume in the layer (%)-real (rfg)

g) lateral saturated hydraulic conductivity (mm/hr)-real (lshc) (read when lsflag=1)

h) vertical saturated hydraulic conductivity (mm/hr)-real (vshc)

i) Number of water content versus pressure point couples-integer (nowcp)

*Line 14: User comment line-character*80, (solcom5)*

Line 14: (repeated for the number of water content versus pressure point couples)

a) pressure (cm of water)-real (pressure)[a]

b) water content (vol/vol)-real (watcon)

Drain.number:

0.1)number of drainage scenarios-(ndrain)[*]

Drain.loop.name (*repeat ndrain times*):

1.1)scenario name, (up to) 8 characters (dname)

Drain.loop.description:

2.1)description, (up to) 55 characters (may be blank)

3.1)description, (up to) 55 characters (may be blank)

4.1)description, (up to) 55 characters (may be blank)

Drain.loop.landuse:

5.1)for use on land type...., integer-(dcont)

1)crop

2)range

4)roads

Note: 'dcont' must be 1, 2, or 4, as forestland does not support drainage.

Drain.loop.drainage: (read when dcont=1; cropland)

6.1)water table management option-integer (drainfl)

1-free drainage

2-controlled drainage

3-subirrigation

***Controlled drainage and subirrigation:** (read when drainfl=2 or 3)*

7.1)ditch bottom width (cm)-real (botwd)

7.2)ditch side slope (cm/cm)-real (sislp)

7.3)number of weir level settings-integer (numwset)

7.4)flag to define whether runoff and drain flow are being collected in the same ditch- integer (rudffl)

1-both are collected in the same ditch

2-they are collected in different ditches (ditch in which drain flow is collected is simulated)

[+]: lines written in italic are modifications to WEPP for WEPP-WTM.

[*]: number of drainage scenario (ndrain) has to be equal to number of overland flow elements (nofe)

Table L.2. Description of drainage section input file of WEPP-WTM[+]. (continued)

(Table L.2 continued)

Weir Set Dates and Depths: *(read when drainfl=2 or 3 and repeated for the number of weir level settings times as described in line 7.3.*

8.1)month of weir setting date-integer (mo)

8.2)day of weir setting date-integer (wday)

8.3)weir setting depth from surface (cm)-real (weset)

8.4)flag to define subirrigation or controlled drainage-integer (sicdfl)

2-controlled drainage

3-subirrigation

9.1)depth to tile drain (m)-real (ddrain)

9.2)drainage coefficient (m/day)-real (drainc)

9.3)drain tile effective radius (m)-real (drefra)

9.4)drain tile diameter (m)-real (drdiam)

9.5)drain tile spacing (m)-real (sdrain)

9.6)Kirkham's equation depth for flow to drains (m)-real (kirkdept)

9.7)initial water table depth (m)-real (iwtd)

Drain.loop.rangeland: (read when dcont=2; rangeland)

Note: no values; drainage for rangeland not yet supported.

Drain.loop.roads: (read when dcont=4; roads)

Note: no values; drainage for roads not yet supported.

Note: Drain.loop values repeat 'ndrain' times

Appendix M

Figure 19 (p:57) from Skaggs (1978)

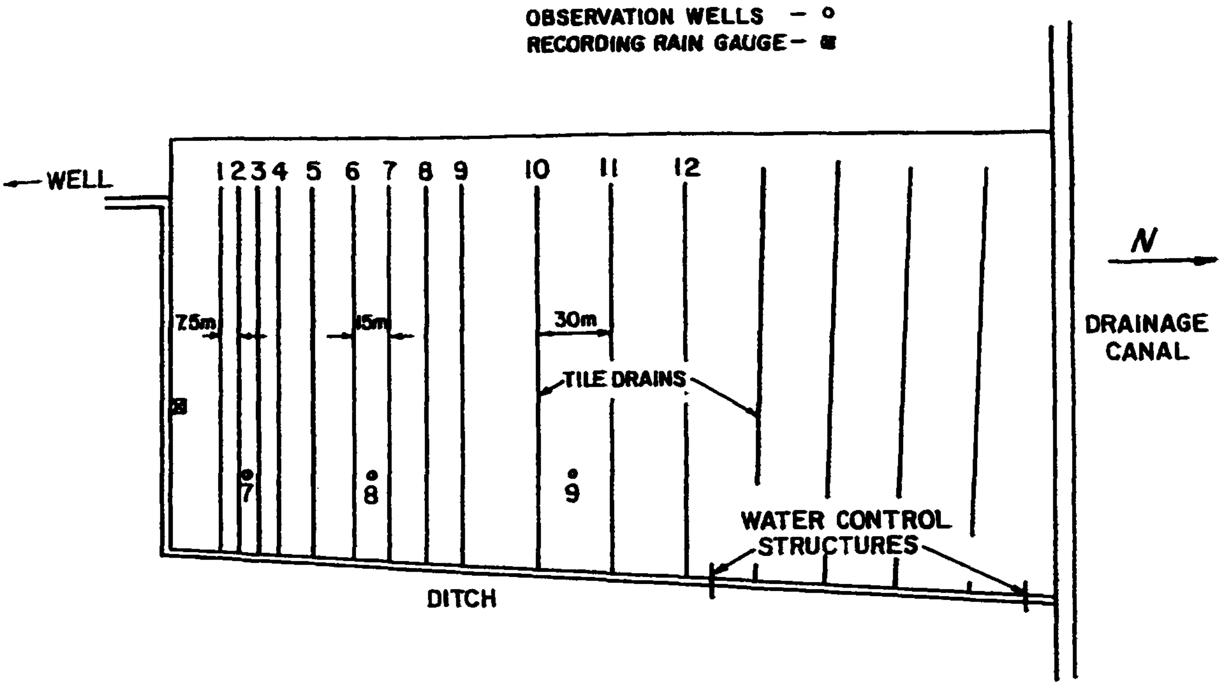

Figure 19. Schematic of experimental setup on the H. Carroll Austin Farm, Aurora, N.C.

Appendix N

The Potential EvapoTranspiration (PET) input file used in WEPP-WTM model for Aurora, North Carolina site (Skaggs, 1978) for 1974.

Aurora, North Carolina PET Input File Used in WEPP-WTMM for 1974

```
PET--nc-74 .081 .051 .007 .020 .018 .007 .034 .031 .027 .060     inches     1
PET--nc-74 .078 .064 .009 .001 .005 .028 .060 .032 .027 .043     inches     2
PET--nc-74 .046 .058 .046 .069 .032 .018 .049 .097 .092 .058     inches     3
PET--nc-74 .057 .053 .034 .063 .029 .003 .002 .025 .034 .003     inches     4
PET--nc-74 .001 .003 .006 .019 .040 .040 .005 .016 .016 .016     inches     5
PET--nc-74 .063 .034 .045 .055 .042 .049 .003 .001 .005 .033     inches     6
PET--nc-74 .070 .085 .097 .110 .110 .105 .143 .124 .083 .093     inches     7
PET--nc-74 .022 .007 .008 .012 .032 .027 .020 .025 .105 .050     inches     8
PET--nc-74 .067 .022 .042 .059 .003 .022 .050 .072 .051 .052     inches     9
PET--nc-74 .067 .136 .129 .132 .159 .088 .028 .042 .101 .042     inches    10
PET--nc-74 .037 .056 .074 .117 .165 .120 .069 .076 .088 .083     inches    11
PET--nc-74 .060 .093 .139 .095 .048 .046 .081 .081 .114 .179     inches    12
PET--nc-74 .194 .176 .108 .122 .119 .061 .113 .131 .094 .128     inches    13
PET--nc-74 .155 .105 .099 .119 .145 .170 .183 .201 .201 .162     inches    14
PET--nc-74 .128 .138 .166 .128 .166 .159 .110 .086 .122 .162     inches    15
PET--nc-74 .170 .177 .210 .161 .165 .130 .161 .173 .165 .144     inches    16
PET--nc-74 .190 .230 .190 .190 .154 .169 .177 .186 .183 .183     inches    17
PET--nc-74 .205 .230 .242 .264 .230 .147 .157 .161 .124 .157     inches    18
PET--nc-74 .173 .187 .218 .231 .224 .174 .215 .199 .170 .206     inches    19
PET--nc-74 .238 .227 .192 .166 .174 .202 .227 .218 .202 .224     inches    20
PET--nc-74 .227 .202 .141 .170 .187 .215 .206 .224 .187 .199     inches    21
PET--nc-74 .215 .218 .201 .186 .201 .204 .189 .160 .156 .183     inches    22
PET--nc-74 .176 .152 .156 .176 .163 .172 .183 .193 .189 .210     inches    23
PET--nc-74 .193 .186 .186 .197 .186 .169 .176 .183 .210 .189     inches    24
PET--nc-74 .228 .225 .225 .196 .174 .168 .185 .140 .128 .162     inches    25
PET--nc-74 .147 .140 .153 .168 .171 .178 .185 .168 .140 .143     inches    26
PET--nc-74 .131 .137 .150 .174 .150 .100 .074 .067 .085 .098     inches    27
PET--nc-74 .116 .140 .134 .071 .082 .040 .021 .031 .061 .089     inches    28
PET--nc-74 .067 .057 .057 .076 .087 .087 .087 .117 .134 .106     inches    29
PET--nc-74 .071 .067 .044 .013 .010 .037 .053 .063 .080 .071     inches    30
PET--nc-74 .061 .084 .091 .093 .090 .100 .103 .110 .113 .113     inches    31
PET--nc-74 .057 .029 .041 .038 .037 .053 .032 .023 .044 .012     inches    32
PET--nc-74 .019 .023 .026 .041 .051 .017 .015 .036 .038 .021     inches    33
PET--nc-74 .002 .005 .010 .012 .014 .029 .006 .010 .010 .006     inches    34
PET--nc-74 .014 .029 .045 .004 .001 .015 .035 .014 .016 .031     inches    35
PET--nc-74 .032 .010 .004 .010 .016 .014 .014 .029 .034 .035     inches    36
PET--nc-74 .005 .016 .015 .027 .038                              inches    37
```

Appendix O

Table 12 (p: 66) from Skaggs (1978)

Table 12. Drainage branch of the soil water characteristics for the soils considered in this study. Values given in table are volumetric water contents.

Soil	Soil water pressure head (cm of water)													Wilting point (15 bars)
	0	-10	-20	-30	-40	-50	-60	-70	-80	-100	-150	-200	-500	
Lumbee s.l. - Aurora														
(0 - 0.6 m)	0.342	0.335	0.322	0.305	0.290	0.280	0.270	0.265	0.256	0.250	0.210	0.190		0.12
Cape Fear l. - Plymouth														
(0.15 m)	0.482	0.444	0.429	0.418	0.410	0.402	0.396	0.392	0.388	0.381	0.372	0.368		0.22
(0.5 m)	0.462	0.444	0.329	0.422	0.417	0.412	0.409	0.405	0.401	0.394	0.378	0.367		
Ogeechee l. - Laurinburg														
(0.3 m)	0.450	0.433	0.420	0.410	0.405	0.402	0.398	0.397	0.391	0.385	0.372	0.365	0.340	0.24
(0.75 m)	0.425	0.398	0.383	0.368	0.358	0.347	0.335	0.331	0.326	0.320	0.312	0.307	0.293	
Goldsboro s.l. - Kinston														
(0.15 m)	0.364	0.354	0.340	0.322	0.300	0.272	0.253	0.242	0.234	0.224	0.192	0.186		0.06
(0.40 m)	0.370	0.360	0.350	0.340	0.326	0.312	0.303	0.297	0.294	0.288	0.282	0.280		
Rains s.l. - Kinston														
(0.15 m)	0.370	0.300	0.282	0.272	0.266	0.258	0.254	0.248	0.244	0.238	0.228	0.224		0.09
(0.40 m)	0.368	0.326	0.302	0.286	0.275	0.267	0.261	0.256	0.251	0.244	0.231	0.222		
Wagram l.s.														
(0-0.9 m)	0.302	0.299	0.285	0.254	0.218	0.184	0.154	0.132	0.117	0.103	0.087	0.072	0.051	0.03
Portsmouth s.l. - Plymouth														
(0.15 m)	0.390	0.363	0.354	0.346	0.340	0.334	0.328	0.324	0.319	0.312	0.304	0.296		0.13
(0.40 m)	0.400	0.382	0.370	0.361	0.354	0.348	0.342	0.338	0.336	0.334	0.331	0.328		

Appendix P

Table 8 (p:54) from Skaggs (1978)

Table 8. Drainage system parameters for the experimental sites.

Parameter	Aurora - Austin Farm			Plymouth	Laurinburg	Kinston	
	7.5 m	15 m	30 m			Rains	Goldsboro
Soil type	Lumbee s.l. (some Myatt)			Cape Fear l.	Ogeechee l.	Rains s.l.	Goldsboro s.l.
Type Drain	clay tile - 4 in.			open ditch	tubing	tubing	clay tile
Drain spacing	7.5 m	15 m	30 m	85 m	48 m	30 m	30 m
Drain depth	0.8 m	0.9 m	1.0 m	0.8 m	1.1 m	1 m	1 m
Drain diameter	102 mm	102 mm	102 mm	open	125 mm	152 mm	102 mm
Effective drain radius	2.5 mm	2.5 mm	2.5 mm	-	7 mm	7 mm	5.1 mm
Depth from drain to restrictive layer	0.5 m	0.5 m	0.7 m	2.2 m	1.4 m	0.4 m	0.4 m
Facilities for water table control							
a. controlled outlet	yes	yes	yes	yes	yes	yes	yes
b. pump-in capability	yes	yes	yes	yes	limited	no	no

Appendix R

Table 11 (p:64) from Skaggs (1978)

Table 11. Summary of K values of profile layers used as input to DRAINMOD.

Site	Layer Depth (m)	K (cm/hr)	Equivalent K* for profile (cm/hr)
Aurora			
7.5 m	0 - 1.0	1.0 cm/hr	
	1.0 - 1.08**	3.0	1.14 cm/hr
15 m	0 - 1.0	1.0	
	1.0 - 1.23**	3.0	1.37
30 m	0 - 1.0	1.0	
	1.0 - 1.58**	3.0	1.73
Plymouth	0 - 1.1	15.0	
	1.1 - 2.82**	45.0	34.0
Laurinburg	0 - 1.20	0.75	3.5
	1.20- 2.40	6.3	
Kinston			
Goldsboro	0 - 1.4	6.5	6.5
Rains	0 - 1.1	4.3	3.6
	1.1 - 1.4	1.0	3.6

*This value is calculated for lateral flow (parallel to the layers) with the water table at the surface.

**Effective depths of the profiles when corrected for convergence near the drain.

Appendix S

Figure 25 (p:69) from Skaggs (1978)

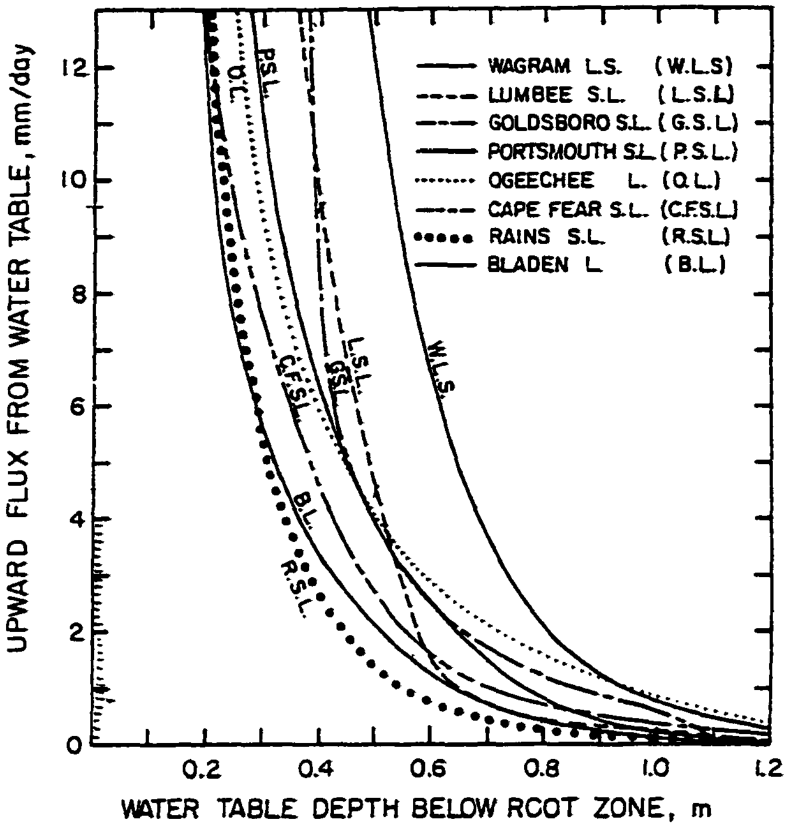

Figure 25. Effect of water table depth on steady upward flux from the water table.

Appendix T

Table 9 (p:55) from Skaggs (1978)

Table 9. Crops grown on research sites; planting and harvesting dates.

	Aurora			Plymouth			Laurinburg		
Year	Crop	Plant date	Harvest date	Crop	Plant date	Harvest date	Crop	Plant date	Harvest date
1973	potato	3-10*	6-20	corn	4-15*	9-12	-	-	-
	soybean	7-17	11-14						
1974	potato	3-10*	6-17	corn	4-15*	10-4	cotton	4-1*	10-15*
	soybean	7-10	11-27						
1975	corn	4-21	9-10	corn	4-21	9-23	cotton	4-1*	10-15*
	wheat	11-12	-						
1976	wheat	-	6-16	corn	4-15	9-1	cotton	4-4*	11-10*
	soybean	6-17	11-17	wheat	12-1	-			
1977	corn	4-25	9-1*	wheat	-	6-18*	cotton	4-5*	10-25*
				soybean	6-20*	11-20*			

*Approximate dates for planting or harvest.

Appendix U

DARA-WRSIS site soil profile descriptions

8/98

DARA SITE - SUBIRRIGATION PLOTS
Soil Profile Description
Paulding Clay

Ap – 0-8 inches; dark grayish brown (10YR 4/2) clay; moist, weak medium angular blocky structure; parting to medium and fine granular structure; clear smooth boundary.

Bg1 – 8-15 inches; dark grayish brown (2.5Y 4/2) clay with 20% coarse (10YR 5/6) distinct yellowish brown 5% mottles and fine pore linings; weak medium prismatic structure parting to medium angular blocky structure; very firm; diffuse wavy boundary.

Bg2 – 17 to 42 inches; dark grayish brown (2.5Y 4/2) clay; weak coarse prismatic structure party to weak medium and fine angular blocky structure; gradual wavy boundary.

Cg – 44 to 48 inches; dark grayish brown (2.5Y 4/2) clay with 15% fine (2.5Y 4/4) pedon stairs; fine laminated lacustive sediments with (10YR 8/2) calcium carbonate coatings on faces of plates.

9/16/98

Soil Profile Description
Roselms Silty Clay

0-9 inches; dark grayish brown (10YR 4/2) silty clay; moderate medium subangular blocky structure; firm; many fine roots; abrupt smooth boundary

9 to 11 inches; brown (10YR 5/3) silty clay loam; fine flatter roots at plate partings; thin patchy light brownish gray (10YR 6/2) silt coatings on faces of peds; clear smooth boundary

11 to 18 inches; brown (10YR 5/3) clay; many fine faint grayish brown (10YR 5/2) and medium distinct yellowish brown (10YR 5/8) mottles; strong medium angular blocky structure; few fine roots; grayish brown (10YR 5/2) coatings on faces of peds; clear smooth boundary

18 to 26 inches; dark grayish brown (10YR 4/2) clay; common fine distinct dark yellowish brown (10YR 4/6) mottles; strong medium angular blocky structure; firm; occasional fine roots; grayish brown (10YR 5/2) coatings on ped faces; clear smooth boundary

26 to 32 inches; grayish brown (10YR 5/2) clay; common fine distinct dark yellowish brown (10YR 4/4) mottles; moderate coarse prismatic structure parting to moderate medium angular blocky structure; few white (10YR 8/2) calcium carbonate coatings; gradual wavy boundary.

32 to 40 inches; gray (10YR 5/1) clay; common fine distinct (2.5Y 4/4) with ped stains, fine laminated lacustrine sediments with white (10YR 8/2) calcium coatings on faces of plates.

Appendix V

Stage-Area-Length data for the wetland at the DARA-WRSIS site, which was used in WEPP-WTM model linked WEPP watershed model.

STAGE-AREA-LENGT DATA USED FOR DARA WRSIS WETLAND

stage (m)	area (m^2)	length (m)
0.0100	0.2000	0.5000
0.0200	0.3000	0.6000
0.0600	13.3300	6.1000
0.1200	71.9100	10.6700
0.1800	129.8800	16.7600
0.2400	200.0300	19.2000
0.3000	271.4100	25.3000
0.3700	341.7700	27.4000
0.4300	415.2800	30.4800
0.4900	489.6900	31.0900
0.5500	569.4900	32.3100
0.6100	640.6000	35.0500
0.6700	715.3900	35.6600
0.7300	795.1800	36.8800
0.7900	876.5800	43.5900
0.8500	960.8200	46.0300
0.9100	1063.6000	49.0700
0.9800	1179.7800	52.4300
1.0400	1309.1300	54.8600
1.1000	1460.4600	57.3000
1.1600	1637.3101	62.4800
1.2200	1846.4000	65.5300
1.2800	2105.0601	73.7600
1.3400	2471.3101	88.3900
1.4000	2944.2600	105.1600

Appendix W

The structure file for the hillslopes, channels, and impoundments (wetland) at the DARA-WRSIS watershed. This file was used in WEPP-WTM linked WEPP watershed model.

```
DARA WRSIS WATERSHED STRUCTURE FILE

97.0
2    2    1    0    0    0    0    0    0    0    # channel 19
2    0    0    3    0    0    0    0    0    0    # channel 20
2    0    0    4    0    0    0    0    0    0    # channel 21
2    0    0    6    0    0    0    0    0    0    # channel 22
2    0    14   0    0    0    0    0    0    0    # channel 23
2    0    13   0    0    0    23   0    0    0    # channel 24
2    0    12   0    0    0    24   0    0    0    # channel 25
2    0    11   0    0    0    25   0    0    0    # channel 26
2    15   10   0    0    0    26   0    0    0    # channel 27
2    0    9    0    0    0    27   0    0    0    # channel 28
2    0    8    0    0    0    28   0    0    0    # channel 29
2    0    7    0    0    0    29   0    0    0    # channel 30
2    0    0    0    0    22   30   0    0    0    # channel 31
2    16   5    0    0    0    31   0    0    0    # channel 32
3    0    0    0    32   20   21   0    0    0    # wetland
2    0    0    0    0    0    0    0    0    33   # channel 34
2    0    0    0    0    19   34   0    0    0    # channel 35
2    17   0    0    0    0    0    0    0    0    # channel 36
2    0    18   0    0    0    0    0    0    0    # channel 37
2    0    0    0    0    36   37   0    0    0    # channel 38
2    0    0    0    0    35   38   0    0    0    # channel 39
```