Spring 2013

The impact of agricultural drainage systems on hydrologic responses

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THE IMPACT OF AGRICULTURAL DRAINAGE SYSTEMS

ON HYDROLOGIC RESPONSES

by

Rebecca Joy Sheler

A thesis submitted in partial fulfillment
of the requirements for the Master of
Science degree in Civil and Environmental Engineering
in the Graduate College of
The University of Iowa

May 2013

Thesis Supervisor: Associate Professor Nandita Basu

Graduate College
The University of Iowa
Iowa City, Iowa

CERTIFICATE OF APPROVAL

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MASTER'S THESIS

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This is to certify that the Master's thesis of

Rebecca Joy Sheler

has been approved by the Examining Committee
for the thesis requirement for the Master of Science
degree in Civil and Environmental Engineering at the May 2013 graduation.

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ACKNOWLEDGMENTS

I would like to extend my appreciation and gratitude to the following:

God for the wisdom and perseverance that has been granted to me during this research project and throughout my life; "I can do everything through Christ who gives me strength." (Philippians 4:13)

Dr. Nandita Basu, for making this research possible. Her guidance, knowledge, and persistence throughout the project is greatly appreciated. Without her direction, I would not have been able to put this work together.

Dr. Larry Weber, for encouraging me along the way to continue challenging myself and exploring my education. The journey has been an interesting and rewarding one.

Last but not least, my husband who has faithfully stood by me every step of the way and my family who supports me unconditionally in every new adventure of life.

ABSTRACT

Over the past century of settlement, the landscapes of the Midwestern United States have experienced extensive anthropogenic modifications in order to convert prior wetlands-lowlands to subsequent fruitful croplands. The hydrologic responses of these landscapes have been significantly altered by the installation of artificial drainage (surface ditches and subsurface tile drains) and the change in natural preferential flow paths (increased cracks or root holes due to land use practices). Changes to peak stream flow behaviors is a result of many different inter-related variables; however, intensified agricultural drainage remains one of the largest suspects. Though the effects of subsurface drainage (primarily in the form of tile drains) on landscape, hydrology, ecology, and economy have been questioned, theories of hydrologic controls continue to be vague at best. Soil-Water-Atmosphere-Plant, known as SWAP, was developed to simulate the interaction of vegetation development with the transport of water, solutes, and heat in the unsaturated zone. It is a one-dimensional, vertically directed model with a domain reaching from a plane just above the canopy to a plane in the shallow saturated zone. In the horizontal direction, the model's main focus is the field scale since most transport processes can be described in a deterministic way. The SWAP model was calibrated and validated for simulating flow regimes of drained and undrained landscapes in Iowa. A new term 'flashiness' is used to characterize flow data. The Richards-Baker Flashiness Index quantifies the frequency and intensity of short term changes in streamflow. From the simulated results, the effect of anthropomorphic modifications to a landscape is determined to be strongly influenced by soil structural properties and hydraulic properties, along with rainfall regimes. Adding subsurface drains to soils with lower hydraulic conductivities, such as clay, tends to reduce peak flows during precipitation events. Conversely, adding drainage to soils with higher hydraulic conductivities, such as sand, increases peak flows. During years with heavy precipitation,

soils with lower permeability show a 'saddle shape' relationship between the flashiness index and the distance between tile drains produces. The lowest point of the 'saddle' determines the ideal drain spacing for mitigating flashiness. When the shrinking and cracking of clay soils is considered, macropores dominate water flow pathways into the soil matrix and tile drains have a minimal effect on the flow regime. The volume of macropores at the surface of the soil profile is indirectly proportional to flashiness index. Independent of rainfall regimes, cropping season, and soil type, subsurface flows of drained landscapes always exceed that of undrained landscapes. Continuance of comprehensive studies of artificial subsurface drainage can produce positive impacts on engineering, economic, and ecological environments.

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INTRODUCTION

1.1 Background

Over the past century of settlement, the landscapes of the midwestern United States have experienced extensive anthropogenic modifications in order to convert prior wetlands-lowlands to subsequent fruitful croplands (Basu et al., 2010). To promote intensive crop yields, subsurface drainage systems have been added to landscapes of soils with low-permeability. Construction of surface ditches and installation of subsurface permeable pipes (also known as tile drains) assist in removing excess water. Most design and management of agricultural drainage use a combination of these two methods. The hydrologic responses of these landscapes have been significantly altered by the installation of artificial drainage (surface ditches and subsurface tile drains) and the change in natural preferential flow paths (increased cracks or root holes due to land use practices). Since the frequency of flash floods has noticeably increased in many regions over the past half century, scientists have been studying possible causes from climatic factors to anthropogenic modifications of landscapes (Wiskow and Van der Ploeg, 2003). Changes to peak stream flow behaviors could be a result of many different inter-related variables; however, intensified agricultural drainage remains one of the largest suspects.

1.1.1 Impact of flow regimes on the environment

Adverse effects of agricultural practices on the ecosystem and water quality of receiving water bodies have been studied extensively over the last few decades (Waters, 1995; Walker et al., 2000; Sharpley et al., 1993; Jordan et al., 1997; Mallin, 2009). Broad categories of these negative effects include poor water quality, excess plant growth, and sporadic fish kills. A study of Chesapeake Bay watersheds in Maryland and Virginia (Jordan et al., 1997) established that the percentage of cropland within the watershed is strongly correlated with the discharge of nitrogen (particularly nitrate). Discharge of nitrogen from this cropland was six times that of forested watersheds (Mallin, 2009). In the Mississippi River Basin, Midwestern states like Illinois, Iowa, and Indiana are known to be large contributors of nitrogen and phosphorus to receiving streams. Excess nitrogen and phosphorus are the main culprits in the eutrophication of surface water. Large zones of hypoxic bottom waters known as "dead zones" in the Gulf of Mexico result from nutrient loading (Goolsby et al., 2000; David et al., 2006; Vidon and Cuadra, 2010). Though climatic factors such as temperature and evaporation have been studied extensively, anthropogenic modifications to landscapes such as agricultural usage and urbanization have been determined to be stronger indicates of algal and chironomid community change in the Canadian Great Plains (Hall et al., 1999). Other negative environmental effects resulting from reduction of wetlands include loss of habitat, altered flow regimes, and suspended sediment from erosion.

When artificial drainage systems are present, nutrient losses from agricultural areas are especially likely to occur. Aquatic problems can be mitigated by reducing nutrient loading to water bodies. Therefore, characterizing the hydrological controls regulating water and nutrient losses is critical in order to mitigate the impact of intensified agricultural practices on water quality and flow regimes.

1.1.2 Agricultural tile drainage systems

Figure 1-1 presents schematics of the four main types of subsurface drainage systems (Pavelis, 1987): corrugated and PVC slotted subsurface pipes (drain tile), mole drains, interceptor drains, and ground water pumps. Drain tile is frequently used in conventional farming practices since installation is relatively simple and inexpensive. Controlling the water table level in the soil profile is typically accomplished by utilizing a drainage system consisting of subsurface permeable pipes (drain tile) which discharge into surface ditches that carry surplus water downstream.

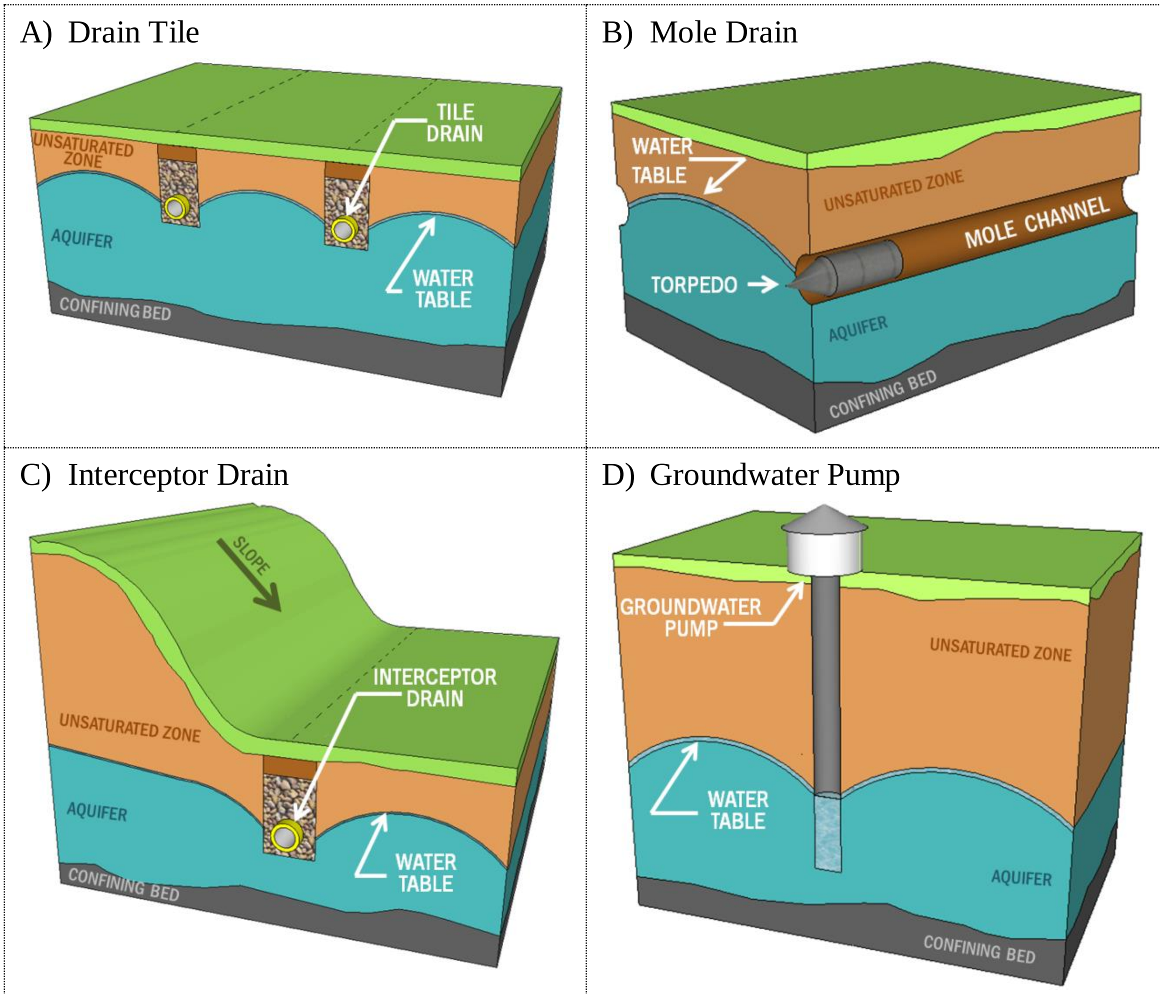


Figure 1-1 Schematics of four common types of subsurface drainage: A) drain tile, B) mole drains, C) interceptor drains, and D) groundwater pumps.

Tile drains were introduced to the United States in 1838 by a Scottish farmer named John Johnston who was later titled “The Father of Tile Drainage in the United States”. In the past, drain tiles were made from short, cylindrical clay sections of pipe and were installed at a depth of three to six feet by manually digging trenches. Cement tiles eventually replaced clay tiles and in the late 1900’s, flexible perforated polyethylene tubing became the new standard of tile drains. Specialized ditching machines can install these lightweight tiles at a record pace.

Land drainage played an integral role in the U.S. Westward Expansion. In the past, the ability to farm was essential for survival. The decades following the American Civil War saw rapid development of drainage systems; more land became suitable for habitation. For example, in 1846 Iowa became the 29th state in the Union but the population remained below average for another 40 years until drain tiles were used to transform wetlands into profitable cropland. Iowa's agricultural industry began as a tool for survival and has developed into the foundation of the state's economy.

Tiles work to drain land by expediting the conveyance of subsurface water to an outlet, typically a surface drainage ditch (Figure 1-2). Water is able to move through the soil matrix at a quicker pace and exit the subsurface rapidly, thereby artificially lowering the water table and increasing the vadose zone. The rooting zone of the cultivated crop is forced to increase to reach the groundwater table. When the soil is not fully saturated, oxygen and other nutrients are able to exist more abundantly in the soil matrix. Therefore, crops with deeper roots naturally have a higher yield potential due to improved access to vital nutrients and water sources. The deep roots also provide more stability during harsh weather conditions. Water-logged soils limit access of heavy machinery to the fields. Since modern agricultural practices rely on heavy machinery in order to remain competitive, access to the site is economically critical and subsurface drainage is instrumental in creating adequate soil conditions for use of heavy machinery.

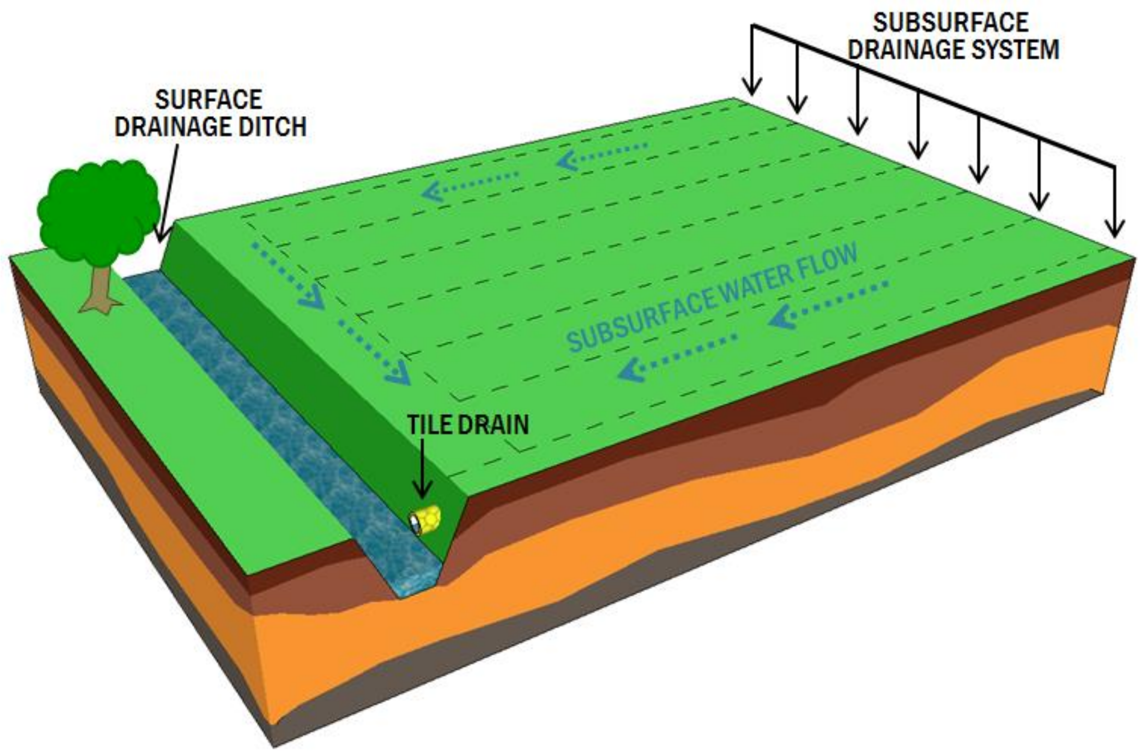


Figure 1-2 Overview of a typical parallel subsurface tile drain system.

Installation of drain tile depends on a range of factors including topography, soil type, and crop rotation. Individual design is necessary to properly install tile in any field and currently, the primary consideration in developing these systems is soil type. In sandy soils, tile drains can be laid further apart since the soil matrix is ‘loose’ and water is naturally able to drain quickly. Clayey soils hold on to water at a higher capacity and therefore, require a shorter distance between tiles in order to drain the vadose zone at an acceptable rate. Though drain tile has become common practice for farmers in many regions across the world, the conclusion of how these tiles impact the hydrology of surrounding systems remains inconclusive. Predicting the flow generated in drain tile from a storm event is central to future work with subsurface drainage systems.

1.2 Previous Work

According to literature, tile drainage and flooding in rivers has been a subject of debate for centuries. Since artificial subsurface drainage plays an integral role in the modern agricultural industry, tile drains have been installed without hesitation for years. Robinson (1990) stated that an explosion of farm drainage hit the United Kingdom in the 1970's and similar booms have occurred in other countries since then. It is well understood that installation of drain tile has a wide ranging effect. The sensitivity of water logging on the site, the worth of the cultivated crops, the size of the landscape being altered, the external costs caused by possible floods, and the increase or decrease of frequency of flash floods (Wiskow and Van der Ploeg, 2003) are a few of the many costs and benefits associated with artificial drainage. Though tile drainage effects on landscape, hydrology, ecology, and economy have been questioned, suppositions continue to be vague at best.

Landscape hydrology during rainfall events is dominated by infiltration when no subsurface drainage is present; after subsurface drainage systems are installed, landscape hydrology is dominated by excessive stream flow and erosion (Knox, 1977; 2001; Trimble and Lund, 1982; Anderson, 2000; Schilling and Libra, 2007). Improved subsurface drainage results in additional phosphorus loss and a reduction of nitrate-nitrogen outflows. Conversely, increased surface drainage results in a reduction of phosphorus loss and additional nitrate-nitrogen outflows. Most literature agrees that tile drainage does increase subsurface flow (lateral flow) across diverse conditions; however, the effects of tiles on peak flows are still highly debated.

Factors such as soil type, rainfall regimes, and topography influence the change in peak flow at the outlet of the watershed. According to Wiskow and Van der Ploeg (2003), drainage systems increase peak flows during large storm events, especially when the system is extensive and large-scale. Skaggs (1994) states "a majority of studies indicate that, compared to natural conditions, drainage improvements in combination with a change in land use to agriculture increase peak runoff rates, sediment losses, and nutrients." Stillman et al. (2006) provides a conditional statement about the role of soil type in the flow regime when tiles are installed. His research states that tile drains facilitate infiltration of rainfall and reduce the amount of surface runoff; however, soils with large cracks or macropores may contribute significantly to streamflow when tile drains are present (Nicholson, 1953; Trafford and Rycroft, 1973; Stillman et al., 2006). Extensive research done by Robinson (1990) further supports this statement.

Although his research was conducted over twenty years ago, Robinson (1990) seems to provide the most insight on the subject of agricultural drainage systems and the effect they have on the hydrologic response. Robinson gathered observed data and simulated predicted data in an attempt to investigate the subject comprehensively. The observed data was collected in England and Wales over six separate sites that qualified for the study. Four of the sites recorded streamflow data from before and after drainage was installed and two of the sites were side-by-side comparisons of drained and undrained plots of land. Initially, the results showed that drainage both increased and decreased peak flow; therefore, site conditions were analyzed. Additional comparisons of the following were investigated for each site: topography of the site, climate regimes, soil properties, pre-drainage soil water regime, and the type of artificial drainage system installed. Robinson deduced that after drainage is installed, peak flow will increase or decrease based significantly on soil characteristics of the landscape.

When drainage reduces downstream flooding, it is in soils that are prone to prolonged surface saturation, such as heavy clay soils (Figure 1-3). These soils are naturally 'flashy' but with drainage the water table is lowered and surface saturation is reduced. During large rainfall events, the soil matrix absorbs and stores more water than it would in natural conditions. Subsurface drainage routes increase travel times of the flow. Since the response or lag times to peak flows are increased, the peak discharges are lower.

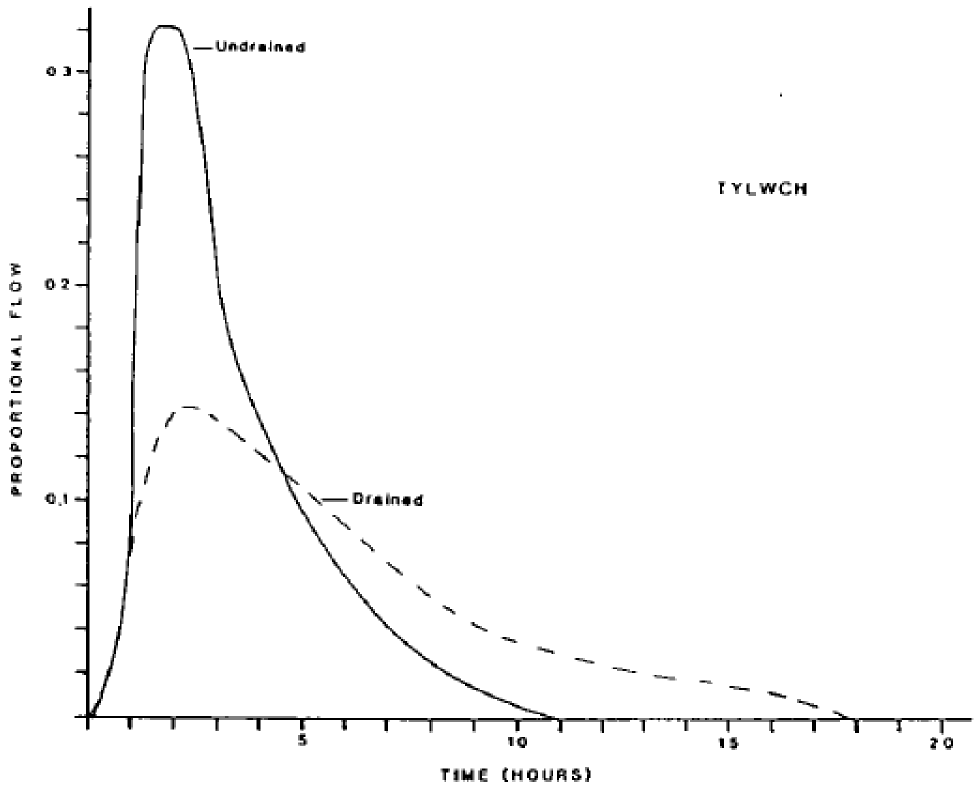


Figure 1-3 Comparison of one-hour average unit hydrographs for periods before and after subsurface drainage at Tylwch (31% clay, 13% sand).

Source: Robinson, M. (1990). Impact of improved land drainage on river flows.

When drainage increases downstream flooding, it is in soils that are less prone to soil saturation and are more permeable, such as sandy soils (Figure 1-4). By adding tile drains, soil saturation is reduced. When the water in the soil matrix of these soils is removed subsurface drainage is able to occur over an increasingly shorter period of time. Travel times decrease causing peak storm flows to occur over a shorter period of time. During dry weather conditions, flow will be decreased since the soil matrix is already unsaturated. Robinson (1990) concludes that the driving factor of change in peak flow due to drainage systems is soil structure.

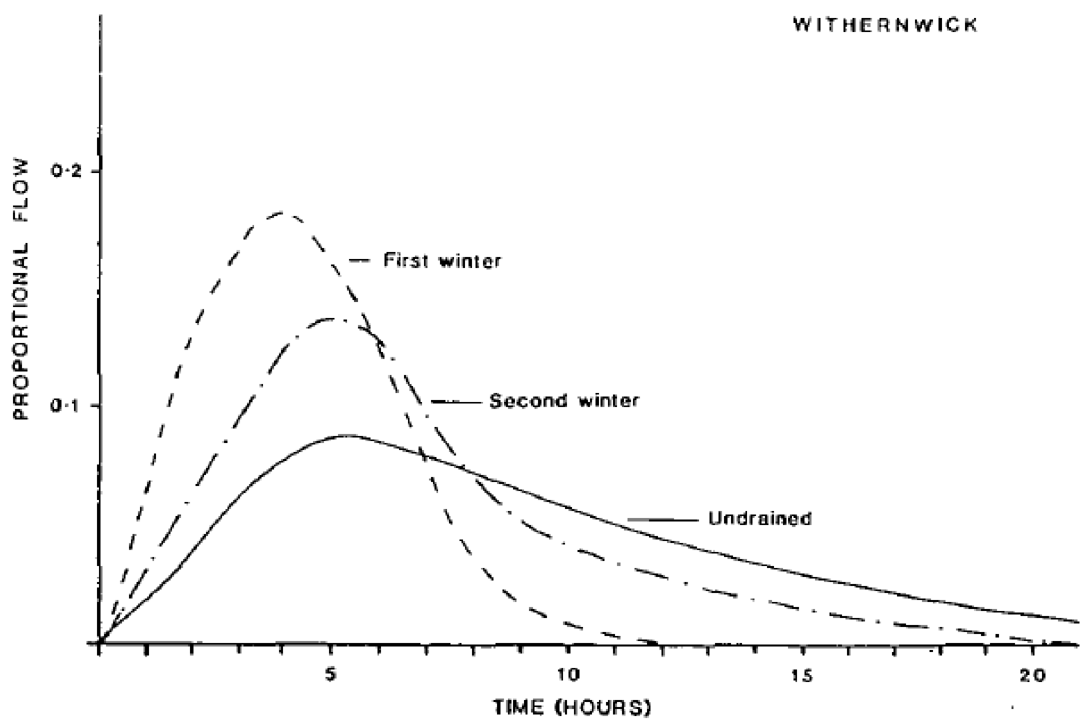


Figure 1-4 Comparison of one-hour average unit hydrographs for periods before and after subsurface drainage at Withernwick (50% sand, 22% clay).

Source: Robinson, M. (1990). Impact of improved land drainage on river flows.

Aside from soil type, tillage practices can drastically affect the structure of a soil. Land use change from grass to arable land will be accompanied by an increase in mechanical agitation. Reduction of peak flows due to plowing has been suspected for decades (Nicholson, 1943), and has been confirmed in more recent studies (Parkinson et al., 1988). Two factors appear to contribute to the effect of plowing. Firstly, macroporosity is increased by tillage (Kuipers and Van Ouwerkerk, 1963); macroporosity promotes infiltration which reduces the surface flow. Secondly, tillage disrupts the vertical continuity of pores in the topsoil directly affected by plowing. This is shown in tracer studies by Douglas et al. (1980) and also Nortcliff et al. (1993). By disrupting this continuity, the rate of downward flow in the subsurface is reduced and the baseflow peaks are also mitigated (Goss et al., 1978; Harris et al., 1984). Robinson goes on to report that "the importance of structural cracks for water movement in clay soils is now widely acknowledged (1990)."

Robinson also makes a clear distinction of pipes versus open ditches in artificial drainage systems. Flow regimes of an open ditch drainage system (surface drainage) have more rapid responses than flows through the subsurface drains. Extra lag time is necessary for the water to travel through the soil matrix before it reaches the subsurface drainage system whereas surface systems bypass the infiltration due to saturation. Discharge data simulated by the computer model DRAINMOD validates the influence of rainfall regimes on flow characteristics (Robinson, 1990). Sites with lower than average rainfall show an overall increase in peak flows with artificial drainage.

1.3 Objectives

After reviewing available literature on the effect of subsurface drainage on altering the hydrologic response, it is even more evident that while general understanding exists regarding the role of rainfall, soil type, and management on agricultural drainage, a quantitative and exhaustive treatment of the question is missing. Given the previous field research performed on the effects of artificial subsurface drainage in landscapes, the logical next step is to explore the range of responses using numerical experiments. Thus, the overall objective of this thesis is to **study the effects of rainfall, soil type, and management of hydrologic response in landscapes with artificial subsurface drainage.** This study's specific objectives are to:

- Review the literature on existing field-scale hydrology models that simulate the effect of subsurface drainage and select one model for the thesis.

- Calibrate and validate the model using observed data at a field site in Iowa.
- Perform simulations of the landscape; investigating the role of rainfall, soil, vegetation, and drainage in altering the hydrologic response.
- Uncover and interpret patterns in the simulated flow regimes from the numerical experimentation to further understand the impact of artificial subsurface drainage on the hydrologic response.

In Chapter 2, a literature review of two hydrologic field scale models is presented along with the theory of physical processes behind the simulation models. Chapter 3 describes the calibration and validation of the hydrologic model. The results of numerical experiments to understand dominant controls on lateral drainage are presented in Chapter 4, and the conclusion of this thesis is stated in Chapter 5.

CHAPTER 2

LITERATURE REVIEW: SWAP AND DRAINMOD MODELS

2.1 Introduction

To predict the subsurface flow in artificially drained landscapes, complex physical interactions between soil profiles, field surfaces, and drainage systems must be understood. Various computer models attempt to simulate these intricate exchanges and provide scientists with accommodating tools. The DRAINMOD model is frequently used in the United Sates. It is a one-dimensional model developed by Dr. Wayne Skaggs in 1980 at the Department of Biological and Agricultural Engineering, North Carolina State University. It is a process-based, distributed, field-scale model that focuses on drainage in soils and predicts the effects of drainage on water table depths, the soil water regime, and crop yields (Skaggs, 1985). Soil-Water-Atmosphere-Plant (SWAP) is a similar model commonly used in Europe. It is a one-dimensional model that simulates the transport of water, solutes, and heat in unsaturated and saturated soils. The model is designed to simulate flow at the field scale. The most recent version of SWAP was developed in the Netherlands by Kroes et al. (2008) and is the successor of the agrohydrological model SWATR (Feddes et al., 1978). Both of these models allow for large sets of data, simulation of tile drains, specific soil properties, and are developed and well tested.

Few previous studies have directly compared the two models. Samipour et al. (2010) provides a direct comparison of SWAP and DRAINMOD. The drainage simulation models were applied to a sugarcane field in Khozestan Province located in South-West Iran in order to determine optimum tile drain management practices. To calibrate and validate these models the following variables were used: soil characteristics, climatological data, irrigation depths and schedules, and water table information. The optimum drain spacing and depths were determined by maximum crop production and minimum drainage water volume. The results show that DRAINMOD had a tendency to underestimate the drainage water while SWAP overestimated it. The optimum drain spacing and depth determined by DRAINMOD were 15 m and 1.15 m respectively; these values determined by SWAP were 25 m and 1.60 m, respectively. The RMSE was 14.85 cm for SWAP and was 20.69 cm for DRAINMOD; it was determined that both models showed satisfactory results in the arid conditions of this case study.

El-Sadek et al. (2000) also researched the validity of both SWAP and DRAINMOD, along with another model known as WAVE. The purpose of this study is to validate a lateral field drainage subprogram that was added to the WAVE model by comparing the results with SWAP and DRAINMOD. The performance of the three models was compared using the resulting water table heads and the drainage fluxes over a 2 year period for soil cultivated with corn and a 5 year period for a bare soil. It is concluded by El-Sadek et al. (2000) that the three models tested are not significantly different when using daily rainfall and evapotranspiration data, along with a few site specific parameters characterizing the local drainage conditions.

Though these two models are similar in many ways, differences between the models suggest a case to further research the validity of practical application for each of these models. This study focuses on the SWAP model and how it predicts the hydrologic impacts of artificially drained landscapes.

2.2 SWAP Theory

Soil-Water-Atmosphere-Plant (SWAP) was developed to simulate the interaction of vegetation development with the transport of water, solutes, and heat in the unsaturated zone. It is a one-dimensional vertically directed model with a domain reaching from a plane just above the canopy to a plane in the shallow saturated zone (Figure 2-1). In the horizontal direction, the model's main focus is the field scale. Most transport processes can be described in a deterministic way at the field scale, assuming homogeneity: one microclimate, one vegetation type, one soil type, and one drainage management system. Upscaling from field to regional systems is possible with geographical information systems (GIS).

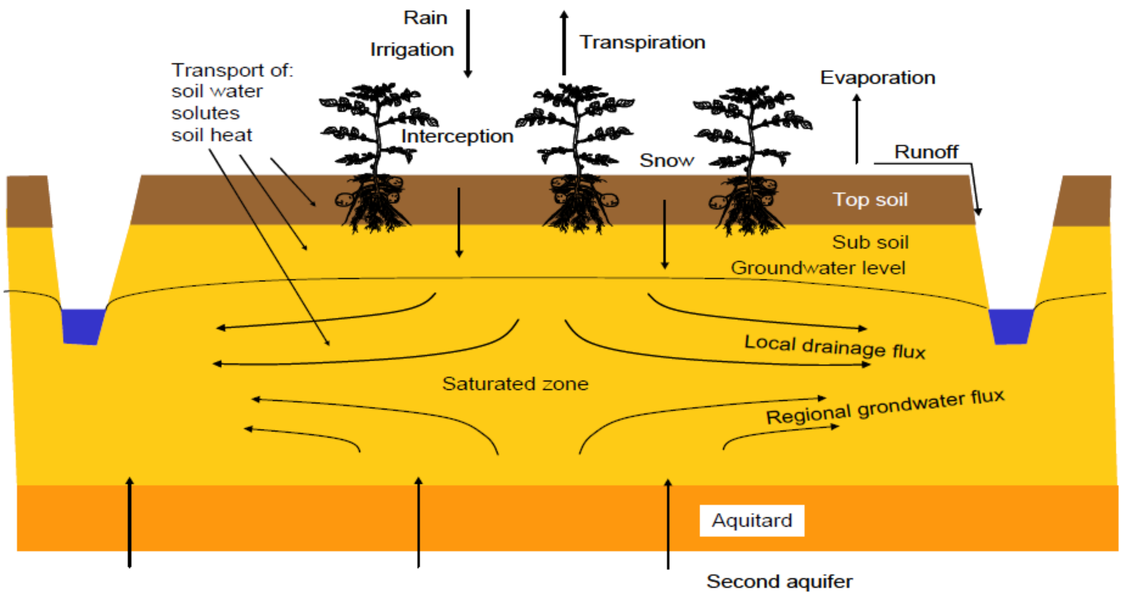


Figure 2-1 Overview of the tranport processes and domain of SWAP.
Source: Kroes et al. (2008). SWAP version 3.2. Theory description and user manual.

Soil water flow is calculated with the Richards' equation and is solved numerically with an implicit, backward, finite difference scheme (the Newton-Raphson iterative procedure). The Richards' equation is a combination of Darcy's equation and the continuity equation for water balance. Darcy's equation and the continuity equation can be written respectively as:

$$q = -K(h)\frac{\partial (h+z)}{\partial z} \tag{2.1}$$

$$\frac{\partial \theta}{\partial t} = -\frac{\partial q}{\partial z} - S_a(h) - S_d(h) - S_m(h) \tag{2.2}$$

where q is soil water flux density (positive upward) (cm d^{-1}), $K(h)$ is hydraulic conductivity (cm d^{-1}), h is soil water pressure head (cm), z is the vertical coordinate (positive upward) (cm), θ is volumetric water content (cm^3 cm^{-3}), t is time (d), $S_a(h)$ is soil water extraction rate by plant roots (cm^3 cm^{-3} d^{-1}), $S_d(h)$ is the extraction rate by drain discharge in the saturated zone (d^{-1}), and $S_m(h)$ is the exchange rate with macropores (d^{-1}). Together, they form the Richards' equation which is the general water flow equation in variably saturated soils;

$$\frac{\partial \theta}{\partial t} = -\frac{\partial \left[K(h)\left(\frac{\partial h}{\partial z} + 1\right)\right]}{\partial z} - S_a(h) - S_d(h) - S_m(h) \tag{2.3}$$

The soil hydraulic functions are defined using the Mualem-Van Genuchten function (Van Genuchten, 1980) with an adjustment for near saturation conditions (Schaap et al., 2001). Numerous studies and several national and international databases (Carsel and Parrish, 1988; Yates et al., 1992; Leij et al., 1996; Wösten et al., 2001) implement the Mualem-Van Genuchten function:

$$\theta = \theta_{res} + (\theta_{sat} - \theta_{res})\,(1 + |\alpha\, h|^{n})^{-m} \tag{2.4}$$

where θ_{sat} is the saturated water content (cm^3 cm^{-3}), θ_{res} is the residual water content in the very dry range (cm^3 cm^{-3}), h is soil water pressure head (cm), and α (cm^{-1}), n (-) and m (-) are empirical shape factors and are described in detail by Kroes et al. (2008).

Hysteresis in the retention function is described by scaling of the main drying and main wetting curves. The bottom boundary can be controlled by different conditions specified by the user. The user can assign a flux, a head, or a combination of both.

SWAP computes the interception for agricultural crops and grasslands according to Von Hoyningen-Hüne (1983) and Braden (1985). They proposed the following formula for canopy interception:

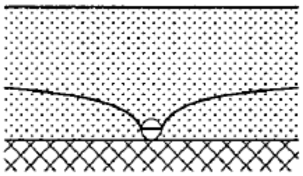
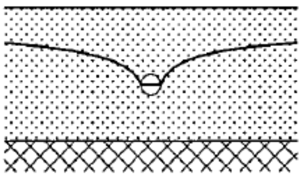
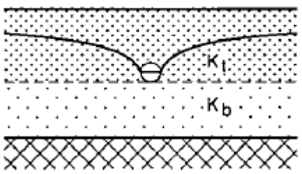
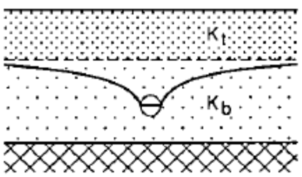
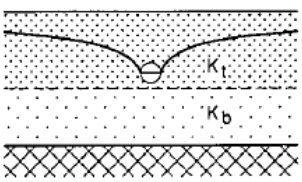
$$P_i = a * LAI \left[1 - \frac{1}{1 + \left(\frac{b * P_{gross}}{a * LAI}\right)}\right] \tag{2.5}$$

where P_i is intercepted precipitation (cm d^{-1}), LAI is leaf area index, P_{gross} is gross precipitation (cm d^{-1}), a is an empirical coefficient (cm d^{-1}), and b represents the soil cover fraction (-). For trees and forests, the Von Hoyningen-Hüne and Braden relationship is not applicable because it asymptotically reaches the saturation amount, $aLAI$, so the concept of Gash (1979; 1995) is implemented instead. There are two methods of calculating evapotranspiration in SWAP. The user may specify reference evapotranspiration and crop factors; however, if enough information is available SWAP implements the Penman-Monteith equation to calculate potential evapotranspiration. This can be applied to wet vegetation, dry vegetation, and bare soil conditions. Once SWAP has calculated potential evaporation and transpiration amounts, actual evaporation and transpiration can be determined taking into account the moisture and salinity conditions in the root zone, the root density, and the capacity of the soil to transport water to the soil surface.

Surface runoff is calculated based on two methods: Horton and Dunne overland flow. Horton overland flow occurs when the rainfall rate exceeds the infiltration rate. Dunne overland flow occurs after the water storage volume of a soil has been exceeded; the groundwater table has reached the surface and infiltration is no longer an available pathway. When the height of the water ponding on the soil surface reaches a critical depth (specified by the user), the Horton method is employed. Interflow is defined as the near-surface flow of water within the soil profile and occurs in the drainage level. Interflow may also occur above the drainage level if the groundwater level rises above that point.

Drainage of a landscape can be complicated and even more difficult to synthetically recreate. SWAP accounts for numerous drainage schemes by providing the user with three input methods. The first method uses the Hooghoudt and Ernst equations. The second method involves the user defining a relationship between drainage flux and groundwater level in a table and the third method involves drainage resistances per system. Drainage fluxes are vertically distributed according to discharge layers in order to determine residence times of solutes. The drainage equations of Hooghoudt and Ernst are based on the drainage flux as a function of the head difference between the drainage level and the maximum groundwater elevation midway between adjacent drains. Ritzema (1994) summarizes the theory behind five drainage situations (Table 2-1) that depend on the position of the groundwater level, the drainage level, and the possible water supplies.

Table 2-1 Characteristics of the five drainage situations modeled in SWAP.

SCHEMATIZATION	SOIL PROFILE	POSITION OF DRAIN	THEORY	EQUATION
	homogeneous	on top of impervious layer	Hooghoudt/ Donnan	$q = \frac{4K(H^2 - D^2)}{L^2}$
	homogeneous	above impervious layer	Hooghoudt with equi-valent depth	$q = \frac{8Kdh + 4Kh^2}{L^2}$
	two layers	at interface of the two soil layers	Hooghoudt	$q = \frac{8K_b dh + 4K_t h^2}{L^2}$
	two layers ($K_t < K_b$)	in bottom layer	Ernst	$h = q(\frac{D_v}{K_t} + \frac{L^2}{8K_bD_b} + \frac{L}{\pi K_b}\ln\frac{D_r}{u})$
	two layers ($K_t < K_b$)	in top layer	Ernst	$h = q(\frac{D_v}{K_t} + \frac{L^2}{8(K_bD_b + K_tD_t)} + \frac{L}{\pi K_t}\ln\frac{aD_r}{u})$

Source: Ritzema, H. P. (1994). Drainage principles and applications (2nd ed.)

The surface water management of the system can be defined in detail with options available for defining different surface water levels, deriving water levels by setting soil moisture criteria (groundwater level, pressure head, minimum storage), and even simulating a weir. The surface water interactions are dictated by a typical water balance formula.

A macropore module has been recently added to SWAP in order to directly characterize the effects of shrinking and cracking of soil by plant roots, soil fauna, or tillage operations. The calculations take into account many physical processes which occur in macropores: infiltration into macropores at the soil surface, rapid transport in macropores to deeper layers, lateral infiltration into and exfiltration out of the soil matrix, water storage in macropores, and rapid flow to drainage systems. SWAP divides macropores into two different domains (Figure 2-2). The main bypass domain is the network of continuous, horizontal, interconnected macropores and the internal catchment domain describes the discontinuous macropores ending at different depths. In addition to the different domains, the model divides macropores by dynamic volumes, which depend on shrinking characteristics, and static volumes. The macropore geometry is described in detail by Hendriks et al. (1999).

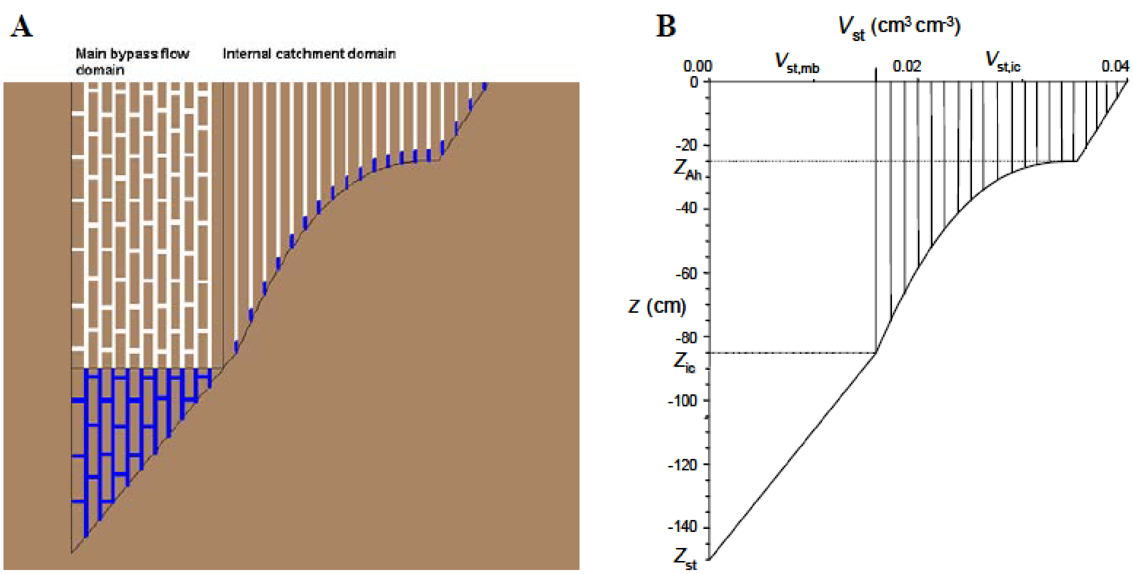


Figure 2-2 Schematic representation of SWAP's macropore module showing A) the profile of the main bypass flow domain and the internal catchment domain and B) the mathmatical description of the two domains as static macropore volume fraction V_{st} as a function of macropore depth.

Source: Kroes et al. (2008). SWAP version 3.2. Theory description and user manual.

Three crop growth routines are presented in SWAP: a simple module, a detailed module for crops, and a detailed module for grass. The simple module sets the crop growth rate and is independent of external stress factors. The detailed crop module for countless different crop types uses the generic crop growth model from World Food Studies (WOFOST). This model, shown in Figure 2-3, simulates photosynthesis and crop development in detail, taking into account growth reductions due to water and salt stress. The absorbed radiation is a function of solar radiation and crop leaf area. WOFOST is currently implemented in the SWAP model but also works as a stand-alone crop model for predicting crop yields at the regional and national scale and for estimating yield changes due to changed conditions (Wolf, 2010). The detailed module for grass is a modified version of WOFOST and is not addressed thoroughly by SWAP.

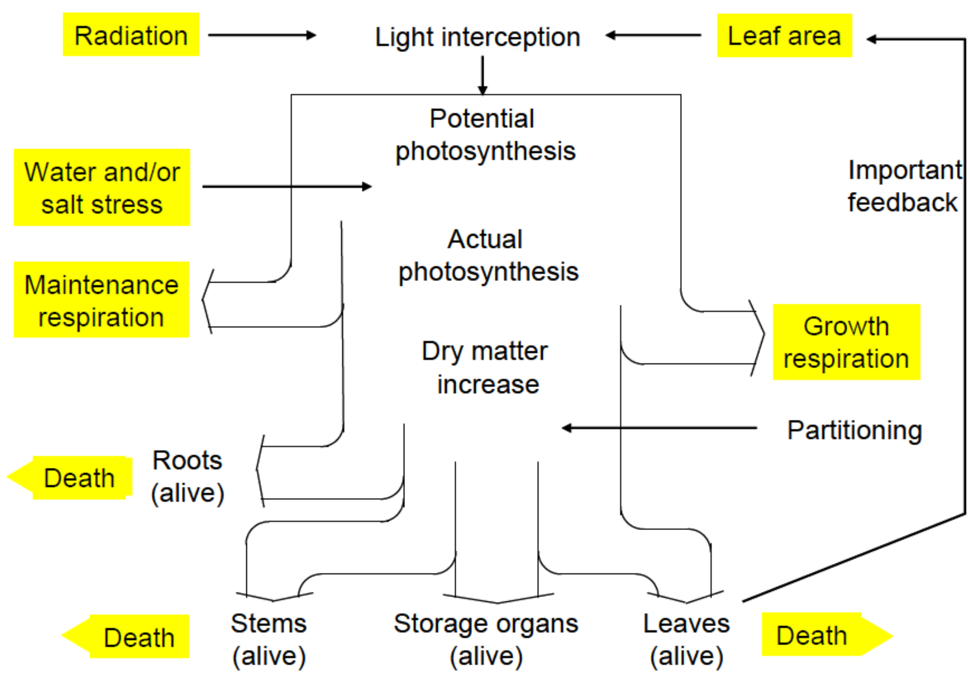


Figure 2-3 Crop growth processes integrated in WOFOST

Source: Kroes et al. (2008). SWAP version 3.2. Theory description and user manual.

Solute transport simulates the transport of salts, pesticides, and other solutes. The transport simulation relies on the basic physical relations of convection, diffusion, dispersion, root uptake, adsorption, and decomposition. Since pesticide transport and nutrient transport are so important for water quality, SWAP can be used in combination with other models such as PESTLA, PEARL, and ANIMO to further explore the transport processes.

At the ground surface, soil temperatures affect many physical, chemical, and biological processes including: the surface energy balance, soil hydraulic properties, decomposition rate of solutes, and growth rate of roots. SWAP simulates soil temperatures both analytically and numerically. In the numerical approach the influence of soil moisture on soil heat capacity and soil thermal conductivity is addressed. In the analytical approach, an input sine function at the soil surface combined with the soil thermal diffusivity is used to simulate soil temperatures.

SWAP can simulate snow and frost or the user can choose to turn off the simulations. When the snow and frost simulations are turned off, soil water and precipitation remain unfrozen. When the snow and frost simulations are running, snow is produced once temperatures dip below a threshold. Snow accumulation and melting are calculated and used in the water balance. Melting occurs when the air temperature rises or heat is released from rainfall. Snowpacks are affected by soil temperature top boundary conditions, insulating effect of snowpacks, and air temperature. Frost is affected by the hydraulic conductivity of the soil, root water uptake, drainage flux, and bottom flux.

Irrigation may be applied with two different regimes in SWAP. The fixed regime is simply defined by the time and depth of water application. The scheduled regime is split and can be defined by either time or depth criteria. Timing criteria include allowable daily stress, allowable depletion of readily or totally available water, critical pressure head, critical moisture content, fixed interval, or minimum intervals. Depth criteria include a user specified ‘back to field capacity’, fixed irrigation depth, and limited depth. Using SWAP, optimal irrigation can be scheduled.

2.3 DRAINMOD Theory

DRAINMOD is a deterministic, hydrologic model developed for the purpose of simulating a soil-regime of drainage landscapes (Figure 2-4). The model predicts surface runoff, infiltration, evapotranspiration, subsurface drainage, and seepage from the soil primarily using a water balance for a vertical soil column of unit surface area. The vertical column ranges from the impermeable layer up to the soil surface.

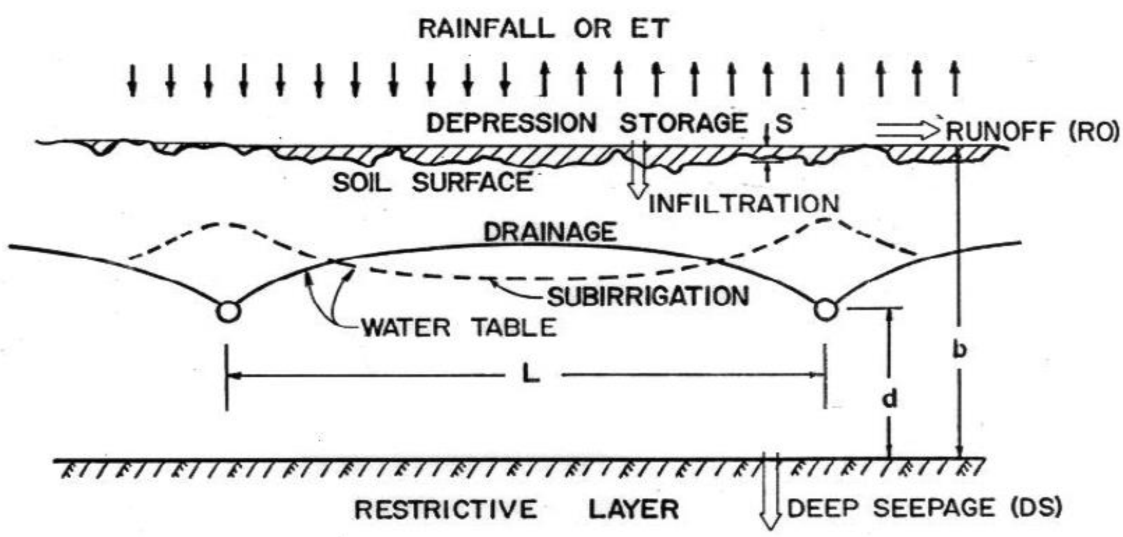


Figure 2-4 Schematic of hydrologic processes simulated by DRAINMOD with subsurface drains that may be used for drainage or subirrigation.

Source: Skaggs, R. W. (1985). DRAINMOD: Reference Report.

SWAP and DRAINMOD use some of the same methods and processes to determine the water flow in surface and subsurface water management systems. The soil utility program in DRAINMOD uses the soil hydraulic parameters from Mualem-Van Genuchten (Mualem, 1976; Van Genuchten, 1980). Tile drainage is simulated using the Hooghoudt and Ernst method focusing on the vertical column of soil located midway between adjacent drains. Soil temperature calculations are performed and soil freeze/thaw cycles are simulated when temperatures allow (Luo et al., 2000; 2001).

Although many of the methods in the two models are similar, the differences of the models need to be addressed further. Instead of using the physically based, non-linear Richards' equation, DRAINMOD relies on the Green-Ampt equation (Green and Ampt, 1911). The Richards' equation requires complex iteration performed over small time steps which can become time consuming depending on the user's computer resources. Many simplified solutions of the Richards' equation have been used over time including the Green-Ampt equation. Green and Ampt assume that as rain continues to fall and water infiltrates, the wetting front advances at the same rate with depth; this produces a well-defined wetting front. Secondly, the volumetric water contents remain constant above and below the wetting front as it progresses downward. Finally, the soil water suction located immediately below the wetting front remains constant with both time and location. As far as the soil water regime is concerned, DRAINMOD does not include a module for macropores in shrinking and cracking soil structures.

Potential evapotranspiration calculation in DRAINMOD is simpler than the Penman-Monteith method used in SWAP. The Thornthwaite (1948) method is used in DRAINMOD and depends on only one climatological factor (the mean air temperature). The Penman-Monteith method uses many climatological factors to calculate potential evapotranspiration: mean air temperature, relative humidity, net radiation, wind speed, saturated vapor pressure, and actual vapor pressure.

Finally, the SWAP methods of predicting crop growth and incorporating the interactions of growing vegetation with the soil water regime are more intricate.

DRAINMOD does allow the user to specify an ‘effective rooting depth’ reference value which is used to define the zone from which water can be removed as necessary to supply evapotranspiration demands. This method is at best an approximation but research is being conducted to develop root and plant growth models for use in DRAINMOD.

DRAINMOD attempts to conceptualize relatively complex physical processes through simplified and approximate methods which may contain a certain extent of error in the model’s predictions for the soil water regime. Also, uncertain input parameters may increase the potential for error. Though the DRAINMOD model is less physically accurate than the SWAP model, DRAINMOD may predict drainage outflows as well or better than SWAP. Since the input variables for DRAINMOD are generally easier to measure or find in literature, this model may be preferred for use in determining the hydrologic effects due to artificial drainage.

2.4 SWAP Model Inputs

The SWAP model is available at no cost and can be downloaded from the developer’s website (www.swap.alterra.nl). The model input consists of four different files and output is generated in ASCII and binary files. The main input file and the meteorological data file are always required in order to run SWAP. The crop growth file and drainage design file are optional.

The main input file contains general information for the simulation including the following: meteorology, crop rotation scheme, irrigation, soil water flow, heat flow, and solute transport. The file starts by defining the environment, the timing of simulation period, the timing of boundary conditions, and choosing which processes should be simulated. Specific vegetation emergence and harvest dates are prescribed in the crop section along with amount and quality of irrigation applications. The soil water section defines the soil properties by layer, initial conditions of the soil, hysteresis of soil water retention function, preferential flow due to macropores, and snow and frost conditions.

All information regarding solute transport is specified in this file: initial conditions, diffusion, dispersion, uptake by roots, adsorption, and decomposition of solutes. The user can also identify the specific parameters to generate for the output files in the main input file.

There are currently three different options for the format of the meteorological data file. When the Penman Monteith formula is used in SWAP, data on solar radiation, air temperature, air humidity and wind speed are required. The daily basic weather data file type will include these values at daily increments. Weather records (including data on solar radiation and air temperature) for short, constant time intervals or detailed rainfall data are the two options for formatting the detailed weather data. In order to properly simulate detailed crop growth, detailed weather data is necessary.

The simple crop growth file should be used when crop development independent of stress factors is sufficient. Typically this model is used when insufficient input data are available or the crop growth impact on soil water movement is of less concern. A detailed crop growth file is required to simulate crop development and biomass assimilation, taking into account growth inhibitors such as water and soil stress. The WOFOST model is used for the detailed crop growth calculations and the input file is divided into 13 parts: crop factor or crop height, crop development, initial values, green surface area, assimilation, conversion of assimilates into biomass, maintenance respiration, partitioning, death rates, crop water use, salt stress, interception root growth, and root density profile.

The drainage design file contains two sections: the basic drainage section and the extended drainage section. The extended drainage section provides input for drainage in regards to surface water levels. The surface water level of primary and secondary systems can be prescribed here along with specific simulation details of the surface water level. If a weir is part of the drainage system, the characteristics will be provided in this section.

The basic drainage section provides input regarding tile drains and ditches and allows the user to select the method used for simulating the drainage. Basic drainage can be calculated based on a table of drainage flux and groundwater level relationship, the drainage formula of Hooghoudt and Ernst, or the drainage and infiltration resistances.

CHAPTER 3

MODEL CALIBRATION AND VALIDATION

3.1 Introduction

The objective of this thesis is to explore climate, soil, and anthropogenic controls on subsurface drainage. To do that, the SWAP model is calibrated for a site in Iowa (Section 3.2) using observed data and DRAINMOD predicted data in a study done by Singh et al. (2006). Then the statistical measures used for the validation process are defined in detail (Section 3.3). Finally, the results of the calibration and validation process of the SWAP model are presented (Section 3.4) in order to show that SWAP is a reliable and accurate tool for predicting the hydrologic responses due to tile drains.

3.2 Model Calibration

Calibration of the SWAP model is necessary in order to validate the hydrological estimates of a drainage system for Iowa's tiled landscapes. A detailed calibration and validation of a field scale deterministic hydrological model, DRAINMOD, has been performed by Singh et al. (2006) in attempts to create a model useful for designing subsurface drainage systems in the Midwest. The study is conducted for two soils found in Iowa: Webster soil cultivated with continuous corn and Canisteo soil cultivated with corn-soybean rotation. The calibration of SWAP follows this procedure closely and identical metrics are used to validate the results.

Although Singh et al. (2006) calibrated DRAINMOD for two different soils present in Iowa, only the Webster soil properties and observations were used to calibrate SWAP. The experimental plots are located near Gilmore City in Pocahontas County, Iowa, USA and span a 4.5 ha area. The drainage system of these plots consists of parallel tiles placed at a depth of 1.06 meters with 7.6 meters between adjacent parallel tiles. The plots with Webster soil were cultivated with continuous corn and the sites were monitored during the growing season (April-November) for 14 years (1990-2003).

Details of the experimental plots and DRAINMOD simulation input parameters are discussed further by Singh et al. (2006).

The crop file for SWAP contains many variables that DRAINMOD does not allow the user to define, therefore the crop file needed to be calibrated for Iowa corn before the calibration procedure described by Singh et al. (2006) could continue. The input of the detailed crop module WOFOST has been divided into 13 different sections; crop factor or crop height, crop development, initial values, green surface area, assimilation, conversion of assimilates into biomass, maintenance respiration, partitioning, death rates, crop water use, salt stress, interception, and root growth/density profile. In order to calibrate the WOFOST model for this project, a specific procedure was followed. The calibration procedure is described in detail by Wolf (2010) and calibrates each of the crop parameters in the following order: length of growth period and phenology, light interception and potential biomass production, assimilate distribution between crop organs, water availability, evapotranspiration, and water-limited production. Once the detailed crop file was calibrated to the Singh et al. (2006) study, the adjustment of the soil hydraulic parameters followed.

3.3 Model Inputs used for Calibration and Experimentation

In the meteorology section, the Penman-Monteith equation is used to calculate the potential evapotranspiration instead of using reference values of evapotranspiration and crop factors. For the calibration procedure, 14 years (1990-2003) of daily meteorological records from Gilmore City, IA are distributed over a prescribed daily duration (6 hours) to match the input of the DRAINMOD model. The solar radiation, temperature, humidity, wind speed, and rain are provided in hourly intervals.

Utilizing the WOFOST module, corn is simulated through the detailed general option in SWAP. The date of crop emergence is set at May 10th for each year and the date of crop harvest is October 17th. The temperature sum from emergence to anthesis is

750 °C and the sum from anthesis to maturity is 859 °C. The initial total crop dry weight is 20 kg ha^{-1} and the initial leaf area index (at emergence) is 0.02604 m^2 m^{-2}. The crop water use is determined by the root extraction method of Feddes et al. (1978). The initial rooting depth is 10 cm and the maximum daily increase in rooting depth is 1.20 cm d^{-1}. The salt stress is not simulated. The interception coefficient of Von Hoyningen-Hüne and Braden is 0.25 cm. No irrigation is applied to the field. The same corn detail is used in all simulations.

The soil water section is contained in the main SWAP file and all conditions must be specified to run the model. The initial soil moisture condition is selected to be dependent on the pressure head of each compartment of soil and is in hydrostatic equilibrium with initial groundwater level (-110 cm). The minimum thickness of ponding needed to produce runoff is 1.25 cm and runon is not simulated. The soil hydraulic functions are described by the Mualem-Van Genuchten parameters. For the calibration process, the soil hydraulic parameters of Webster soils are used from Singh et al. (2006). No hysteresis is simulated. Preferential flow due to shrinking and cracking is switched on and off in the experimental section of this study in order to understand the impact of simulating macropores. The macropores are described by their geometry and the default values are mostly used. Frost, snow accumulation, and snow melt are not simulated. There is no solute transport simulated and the bottom flux is equal to zero.

This study uses the Hooghoudt and Ernst equations to simulate drainage routines. The soil profile is homogeneous and the tile drains are above an impervious layer, therefore, the ‘Hooghoudt with equivalent depth’ theory is employed (Table 2-1). Simulation of drainage with a basic drainage routine is applicable since no surface water management is necessary. The drainage formula of Hooghoudt is used with tiles spaced at 7.6 m for the calibration procedure. The wetted perimeter of each drain is 9.425 cm and the level of the bottom of the tile drain is -106 cm below the soil surface. The drain entry resistance is based on soil type. The horizontal hydraulic conductivity is estimated as the vertical hydraulic conductivity multiplied by 1.4 (Singh et al., 2006). Samples of all four input files are provided in the Appendix.

3.4 Statistical Measures used for Validation

To ensure quality and reliability, certain statistical measures can be used to quantify the differences between the observed and predicted data. The performance of DRAINMOD and SWAP to predict subsurface drainage was evaluated using four metrics: root mean square error (RMSE), coefficient of residual mass (CRM), index of agreement (IoA) (Willmott, 1982), and model efficiency (EF) (Nash and Sutchliffe, 1970). They are as follows:

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(P_i - O_i)^2} \tag{3.1}$$

$$\mathrm{CRM} = \frac{\sum_{i=1}^{N} P_i - \sum_{i=1}^{N} O_i}{\sum_{i=1}^{N} O_i} \tag{3.2}$$

$$\mathrm{IoA} = 1 - \frac{\sum_{i=1}^{N}(P_i - O_i)^2}{\sum_{i=1}^{N}(|O_i - O| + |P_i - O|)^2} \tag{3.3}$$

$$\mathrm{EF} = \frac{\sum_{i=1}^{N}(O_i - O)^2 - \sum_{i=1}^{N}(P_i - O_i)^2}{\sum_{i=1}^{N}(O_i - O)^2} \tag{3.4}$$

where N is the total number of observations, O_i is the observed value of the ith observation, P_i is the predicted value of the ith observation, and O is the mean of the observed values.

3.5 Calibration and Validation Results

The first four years of observed data were used to calibrate and the remaining ten years were used to validate both models. By manipulating the most uncertain and sensitive parameters (soil hydraulic parameters for Webster soils), the difference between the observed and predicted monthly subsurface drainage could be diminished.

The root mean square error (RMSE) is frequently used to measure the difference between observed and predicted values as it is an effective measure of accuracy. However, RMSE is scale-dependent and does not give the relative size and nature of the error. The overall value of RMSE is 1.34 cm for DRAINMOD and 2.03 cm for SWAP. The coefficient of residual mass (CRM) shows the model's tendency of over and under prediction. A positive value shows an over prediction while a negative value shows an under prediction. The overall value of CRM is -0.04 for DRAINMOD and 0.09 for SWAP. Neither models show a systematic over- or under-prediction. The index of agreement (IoA) developed by Willmott (1981) measures the degree of model prediction error and varies between 0 and 1. When the model predicts observed subsurface drainage amounts well, the IoA is closer to 1.00. DRAINMOD had an overall value of 0.97 and SWAP had an overall value of 0.93 for the IoA. Both models show that the additive and proportional differences in the observed and simulated means and variances are acceptable; however, extreme values due to the squared differences within the formula make the IoA an overly sensitive metric. The model efficiency (EF) (Nash and Sutchliffe, 1980) evaluates the error relative to the natural variation of the observed values. Values can vary from $-\infty$ to 1.00; values of $0.50 < EF < 1.00$ are considered acceptable (Helweig et al., 2002; Wang et al., 2006). The overall value of EF is 0.89 for DRAINMOD and is 0.73 for SWAP. Using these four metrics to calibrate the models, DRAINMOD and SWAP show good agreement between the predicted and simulated monthly surface drainage for Webster soils and these values are presented in Table 3-1. Furthermore, the predicted and observed monthly values are plotted 1:1 (Figure 3-1) and confirm the successful calibration.

Table 3-1 Statistical performance of DRAINMOD and SWAP to predict the observed subsurface drainage (cm) for calibration years.

		DRAINMOD				SWAP			
Year	N	RSME	CRM	IoA	EF	RSME	CRM	IoA	EF
1990	4	1.62	-0.17	0.98	0.91	3.33	0.05	0.91	0.64
1991	7	0.76	0.09	0.99	0.96	1.73	0.32	0.97	0.81
1992	9	1.36	-0.21	0.91	0.65	1.12	-0.01	0.93	0.76
1993	7	1.58	0.06	0.95	0.81	1.93	0.00	0.93	0.72
Overall	27	1.34	-0.04	0.97	0.89	2.03	0.09	0.93	0.73

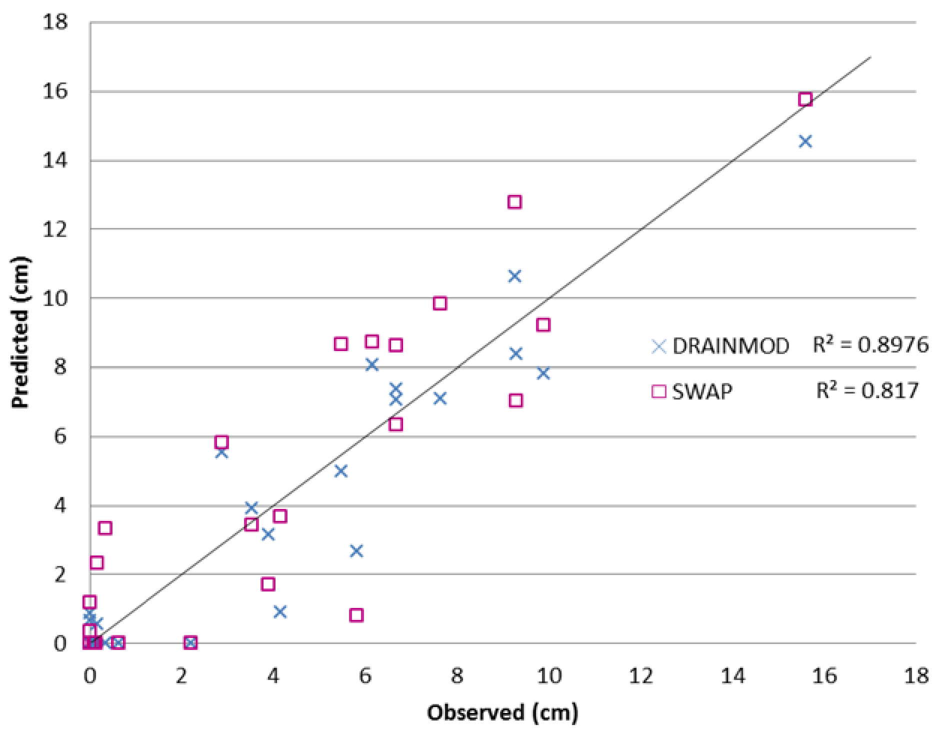


Figure 3-1 Observed and predicted subsurface drainage flows during calibration years (1990-1993).

Both models are expected to perform well during calibration years since input parameters were manipulated to obtain minimal differences between observed and predicted subsurface drainage. The same metrics were used to validate the overall performance of SWAP and then compared to the results of the DRAINMOD model. The overall values of RSME, CRM, IoA, and EF for SWAP are 5.43, 0.22, 0.93, and 0.73 respectively (Table 3-2). A 1:1 plot of observed and predicted values is also presented below (Figure 3-2). Compared with SWAP, DRAINMOD consistently performs marginally better in terms of all four metrics; however, both models show acceptable agreement with observed values.

In addition to these metrics, Figure 3-3 visually compares overall values of subsurface drainage. Performance evaluation is a judgment of whether the model sufficiently represents the system, in its final analysis. SWAP predictions for the subsurface drainage of this landscape falls within acceptable ranges and the model performs a water balance for every time step.

Table 3-2 Values of measured and predicted (DRAINMOD and SWAP) subsurface flow (cm) over a period of 14 years.

Year	Observed	DRAINMOD Predicted	SWAP Predicted
1990	27.2	22.7	28.5
1991	23.6	25.8	31.3
1992	17.0	13.4	16.9
1993	32.8	34.7	32.9
1994	3.3	2.6	3.3
1995	3.6	6.6	9.9
1996	15.4	11.0	5.9
1997	0.1	4.0	5.6
1998	8.2	6.8	7.8
1999	2.0	5.9	7.8
2000	1.8	0.5	0.0
2001	13.2	18.7	20.2
2002	10.3	6.3	11.9
2003	20.8	23.8	29.4
RMSE		3.36	5.43

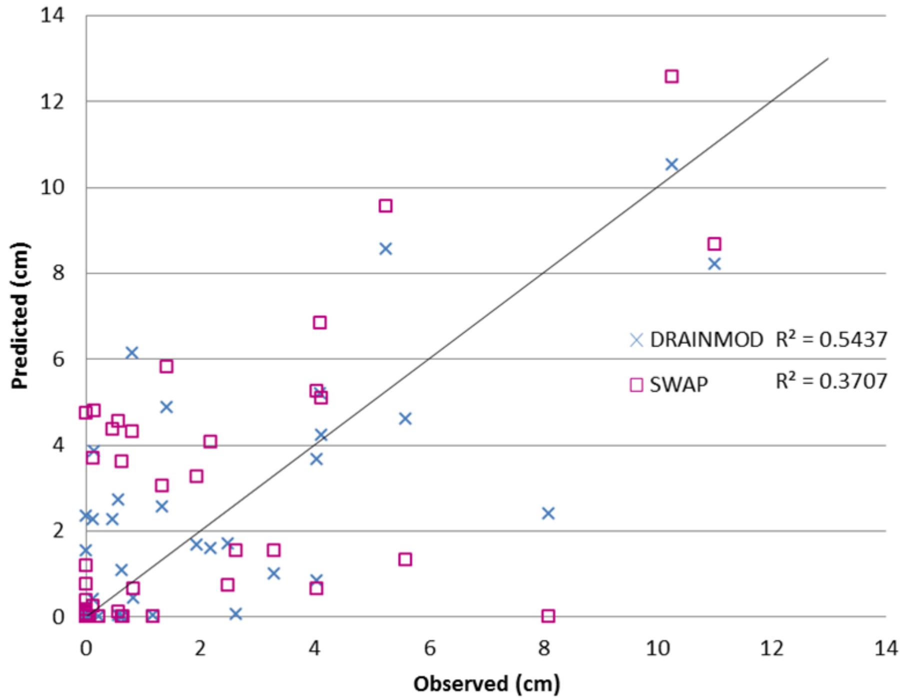


Figure 3-2 Observed and predicted subsurface drainage flows during validation years (1994-2003).

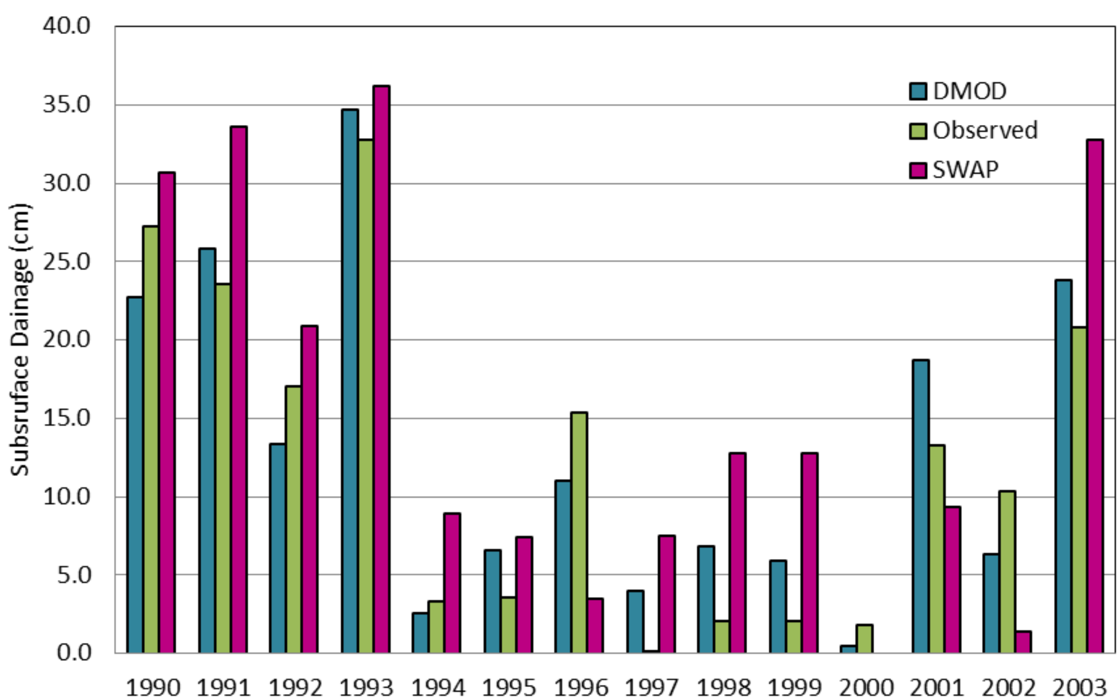


Figure 3-3 Annual sum of observed and predicted (SWAP and DRAINMOD) subsurface drainage.

CHAPTER 4

NUMERICAL EXPERIMENTS TO UNDERSTAND DOMINANT CONTROLS ON TILE RESPONSE

4.1 Introduction

The point of this study is to determine the effect of main controls of the soil water regime on the hydrologic response during storm events. First, the landscape controls are studied by altering the soil type and the soil structure over a period of 26 years of meteorological data (Section 4.2). The hydrologic response of landscape controls are compared before and after tiles are installed. Second, in Section 4.3, the climate controls are simulated by applying low, medium, and high rainfall years over the different soil types before and after tiles are installed. Third, the anthropogenic controls are investigated by altering the distance between adjacent parallel tile drains over the 26 year period and different soil types (Section 4.4). Finally, Section 4.5 attempts to determine patterns of hydrologic response due to the interplay of all three controls: landscape, climate, and anthropogenic (Figure 4-1).

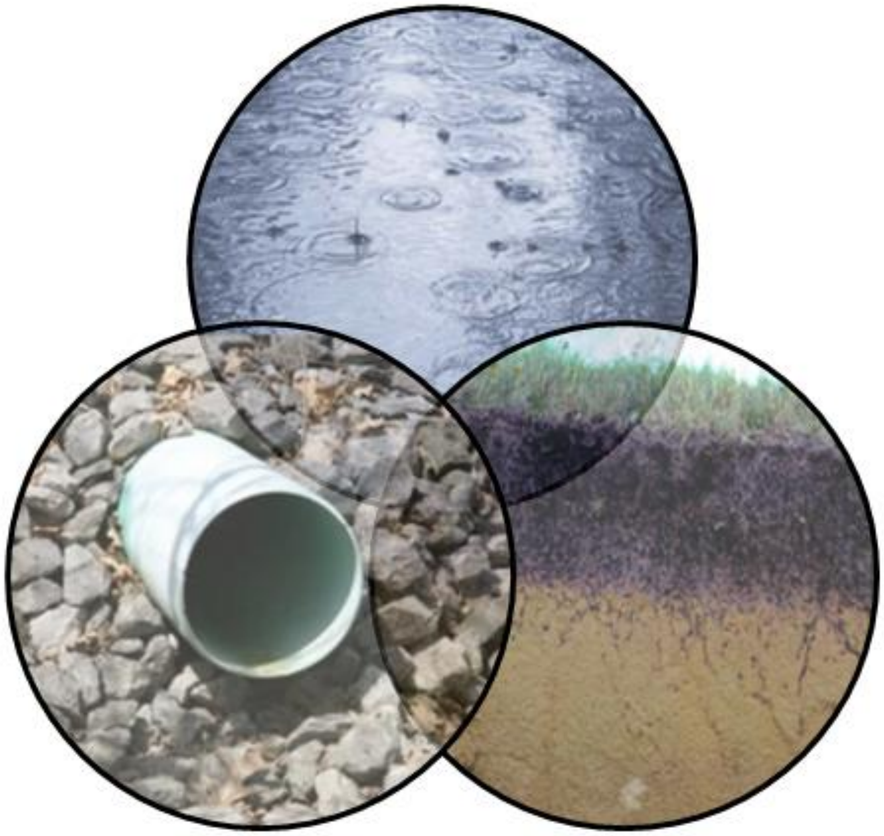


Figure 4-1 Representation of the interplay of the three controls in this study: climate controls, anthropogenic controls, and landscape controls.

Sources: http://www.teara.govt.nz/files/, http://www.earthtimes.org/newsimage/, http://img.ehowcdn.com/article-new/ds-photo/getty/article/

4.1.1 Data sources for numerical experiments

The first control that that was explored on subsurface drainage is the soil type. For this purpose, the soil types in Iowa were determined using the Soil Survey Geographic Database (SSURGO). With SSURGO, the soil map of Iowa was generated and the soils were described in detail. The soil types spanning the largest areas were identified on the map of Iowa (Figure 4-2).

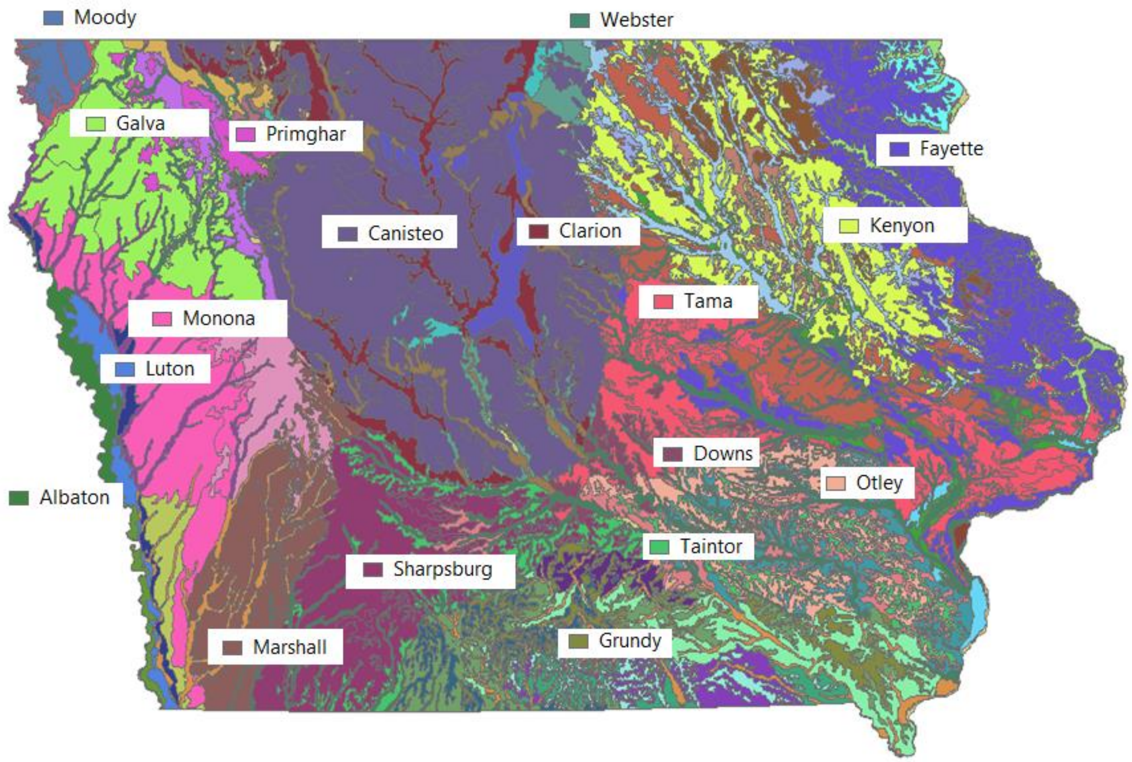


Figure 4-2 SSURGO database showing the eighteen prominent soil types found in Iowa.

The USDA textural classification describes soils by the percentage of each mineral (sand, silt, clay) found in the soil profile. Soil textures are commonly visualized in a trilinear plot with each of the corners representing 100% of sand, silt, or clay (Figure 4-3). The soil types found in Iowa according to the SSURGO database are plotted on this trilinear plot. They primarily fell into the following textural classes: loam, clay loam, silt loam, silty clay, and silty clay loam.

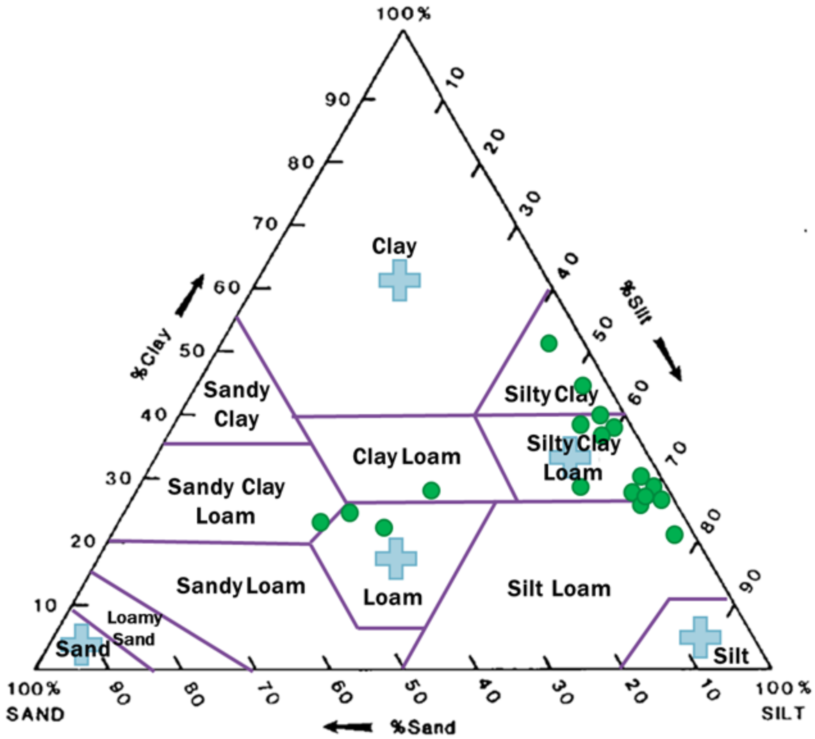


Figure 4-3 Trilinear plot of USDA soil textural classes showing clay, sand, and silt percentages by weight. Circles indicate soils prevalent in Iowa while plus shapes indicate class averaged properties used in analysis.

Since our objective was to explore the effect of a range in soil types, we selected five soil types that are included in the SWAP database. The soil types span a range of values in their hydraulic properties. SWAP requires each soil to be defined by its soil hydraulic parameters for use with the Van Genuchten theory. The residual water content, θ_{res} (cm^3 cm^{-3}), and saturated water content, θ_{sat} (cm^3 cm^{-3}), are defined in the main input file for SWAP under the soil hydraulic function section. The saturated vertical hydraulic conductivity K_{sat} (cm d^{-1}) along with the empirical shape factors such as α (cm^{-1}) of the main drying curve, the shape parameter n (-), and the exponent in the hydraulic conductivity function λ (-), are defined here as well. These parameters are often difficult to measure in the field due to practical or financial constraints. Using a computer program, specifically ROSETTA, to simulate soil hydraulic parameters is a common practice for obtaining these values (Schaap et al., 2001). ROSETTA is able to estimate Van Genuchten (1980) parameters based on Mualem's (1976) pore-size model. The class averaged hydraulic parameters are tabulated in Table 4-1 for each of the twelve USDA textural classes. The ROSETTA class averaged hydraulic parameters for clay, loam, sand, silt, and silty clay loam are used as inputs in the main file (.swp) in attempt to estimate the distinct function of these five soil structures in combination with artificial drainage systems.

Table 4-1 Average soil hydraulic properties of USDA soil textural classes.

Textural Class	θ_{res} (cm^3/cm^3)	θ_{sat} (cm^3/cm^3)	α (1/cm)	n	K_{sat} (cm/hr)	λ
Clay	0.098	0.459	0.015	1.25	0.615	-1.531
Clay Loam	0.079	0.442	0.0158	1.42	0.341	-0.763
Loam	0.061	0.399	0.0111	1.47	0.502	-0.371
Loamy Sand	0.049	0.390	0.0348	1.75	4.383	-0.874
Sand	0.053	0.375	0.0352	3.18	26.779	-0.930
Sandy Clay	0.117	0.385	0.0334	1.21	0.473	-3.665
Sandy Clay Loam	0.063	0.384	0.0211	1.33	0.549	-1.280
Sandy Loam	0.039	0.387	0.0267	1.45	1.595	-0.861
Silt	0.050	0.489	0.0066	1.68	1.823	0.624
Silty Clay Loam	0.111	0.481	0.0162	1.32	0.401	-1.287
Silty Clay	0.090	0.482	0.0084	1.52	0.463	-0.156
Silt Loam	0.065	0.439	0.0051	1.66	0.760	0.365

Observed weather data collected in Ames, Iowa from the Iowa Environmental Mesonet (IEM) is used in this study. The Iowa State Department of Agronomy assembled this mesonet which collects environmental data from cooperating members with observing networks. Twenty-six years of weather data were gathered from 1987 to 2012 at hourly intervals and reformatted to ASCII standards. SWAP is capable of handling inputs of up to 70 years in one execution. The detailed weather input file consists of the date and record number (1 through 24), solar radiation (kJ m^{-2}), air temperature (°C), air humidity (kPa), wind speed (m s^{-1}), and rainfall (mm).

Subsurface tile drains are simulated in a parallel pattern from 5 to 30 m apart and at a depth of 1.06 m. The drain entry resistance (d) varies by soil type and is obtained by dividing the wet perimeter of the channel walls by the hydraulic conductivity. The depth to impermeable layer is 390 cm.

4.1.2 Metrics used for analyzing the alteration of hydrologic response

A flow regime is a pattern of variation of streamflows over a period of time. The flow regime consists of frequency and intensity of floods and low flow periods, the seasonal occurrence of a number of flow rates, and the rates of change of flow. Discharge variables include the total annual discharge, maximum annual discharge, minimum annual discharge, annual baseflow discharge, and annual baseflow percentage. Though these indicators have been used for decades, Baker (et al., 2007) proposes a new approach to characterize the flow by integrating several flow regime characteristics associated with the concept of stream flashiness. Most flow regime indicators vary from year to year; this index normalizes annual variability, making trends easier to discover. While statistically significant trends are not always present in other indices, these trends may be present in the R-B index. Applications of the R-B Index range from analysis of stable/flashy continuums to ecoregional patterns of stream flashiness (Baker et al., 2001).

The term ‘flashiness’ refers to the frequency and intensity of short-term changes in streamflow. These abrupt changes to the flow regime are especially apparent during storm events. Increased or decreased stream flashiness is an indicator of hydrological alteration. Baker (et al., 2007) presents a newly developed flashiness index which is based on mean daily flows and is determined by dividing the pathlength of flow fluctuation for a time interval by total discharge during that period of time. The time interval is typically day-to-day over a period of time, usually around one year. The Richards-Baker Flashiness Index (R-B index) is as follows:

$$R - B\ Index = \frac{\sum_{i=1}^{N} |q_i - q_{i-1}|}{\sum_{i=1}^{N} q_i} \tag{3.1}$$

where q_i and q_{i-1} are the daily discharge volumes (m^3) or average daily flows ($m^3\ s^{-1}$) depending on preference; the value of the index remains the same.

4.2 Landscape Controls on Subsurface Drainage: Soil Type and Macropores

This section investigates the role soil type and macropores play in subsurface drainage. Five different soil textures are studied over 26 years of rainfall. The effects of subsurface drainage on flow partitioning and peak flow attributes are examined for each soil type by comparing lateral flow before and after tile installation. The shrinking and cracking of clay soils are simulated and evaluated by comparing the lateral flow caused by macropores to the subsurface drainage due to tile drains in clay.

4.2.1 Effect of subsurface drainage on flow partitioning as a function of soil type

Water enters the soil-water-plant system in the form of rainfall and exits the system by one of the following pathways: interception, evapotranspiration, surface runoff, and lateral flow. The water balance for the four different soil types (clay, loam, silt, and sand) under drained and undrained conditions is presented in Table 4-2. These results show annual water balance averages based on 26 years of simulations. The drained landscapes consist of subsurface tile drains spaced at 20 m in a parallel configuration, which is a typical spacing for the Midwest (Love, 2013). The most significant effect of subsurface drainage is the partitioning of the flow between surface runoff and subsurface lateral flow. Except for the sandy soil (which has an order of magnitude higher horizontal hydraulic conductivity, K), for all soil types the discharge is dominated by surface runoff prior to drainage. Post drainage surface runoff is minimal, and lateral flow dominates in all soil types. Before drainage, surface runoff ranges from 5% to 23% of the outflow and lateral flow ranges from 1% to 29%. After tile drains are installed surface runoff varies from 0.1% to 9% and lateral flow from 21% to 29% of the outflow. The average interception remains relatively unresponsive to changing soil types and drainage management. The results indicate that the hydraulic conductivity of the soil is a strong control on the flow partitioning and how it responds to drainage.

Table 4-2 Partitioning of water balance components of drained and undrained soils (average annual sums of 26 years of data) normalized by surface area.

Partitioning	SI CL Loam		Loam		Clay		Silt		Sand	
	Undrained (mm)	Drained (mm)	Undrained (mm)	Drained (mm)	Undrained (mm)	Drained (mm)	Undrained (mm)	Drained (mm)	Undrained (mm)	Drained (mm)
Precipitation	663	663	663	663	663	663	663	663	663	663
Interception	16	19	16	19	17	19	17	20	18	21
Evapotranspiration	491	452	489	450	490	452	485	445	417	440
Surface Runoff	151	71	152	69	149	66	139	33	35	1
Lateral Flow	8	125	9	129	10	129	25	168	194	205

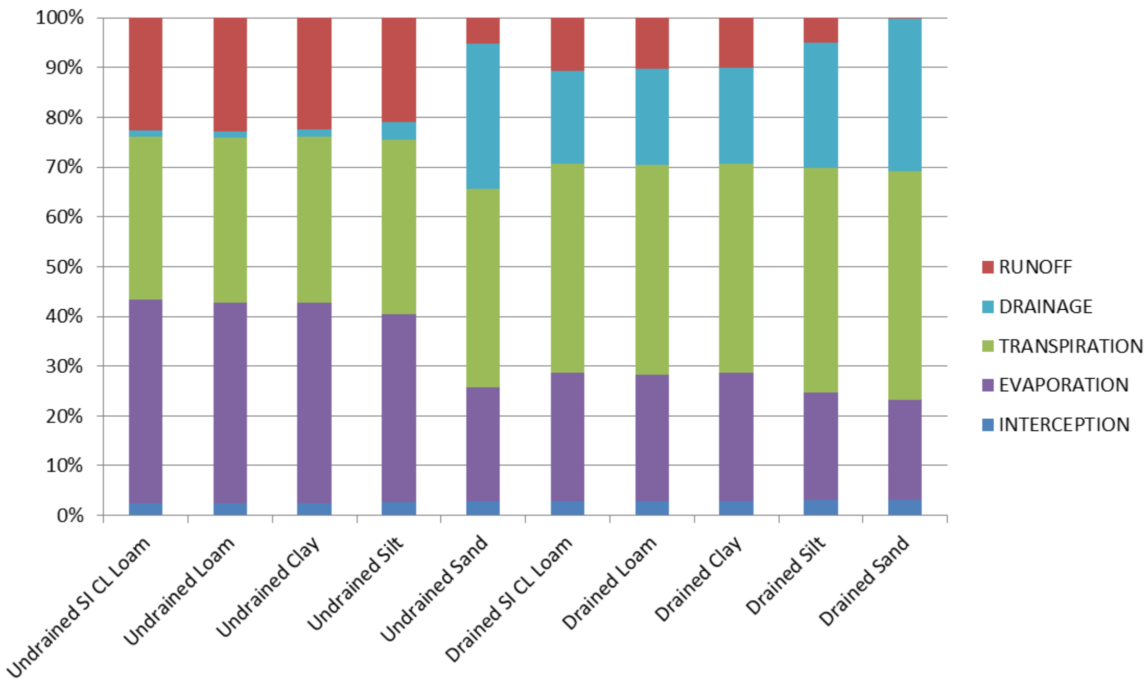
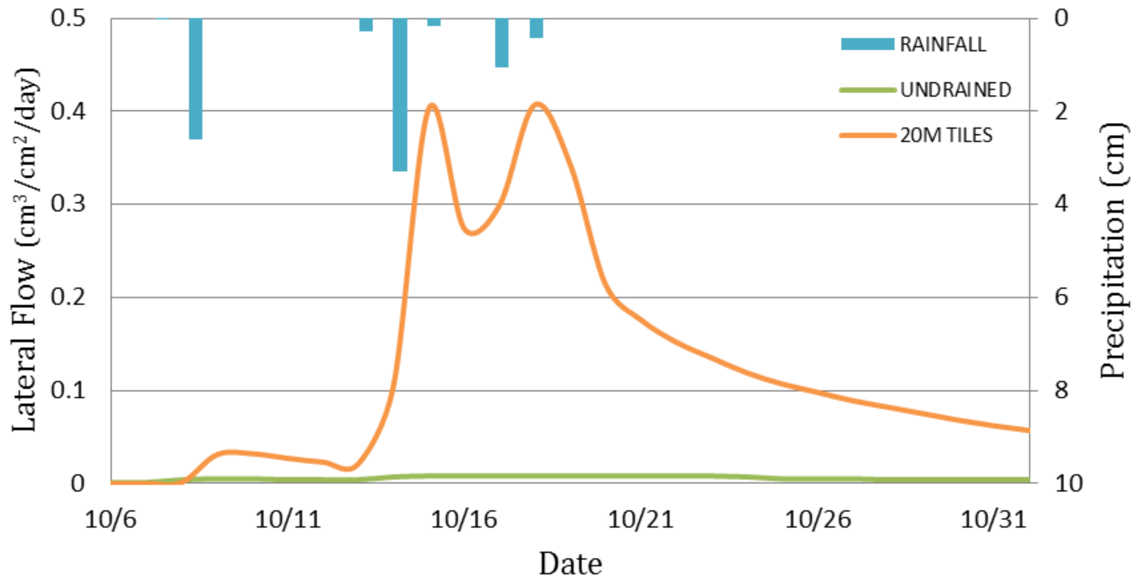


Figure 4-4 Visualizing the partitioning of water balance components of undrained and drained soils (average annual sums of 26 years of data) normalized by surface area and listed in order of increasing hydraulic conductivity ($K_{si\ cl\ loam}$ = 13 cm d^{-1}, K_{loam} = 17 cm d^{-1}, K_{clay} = 21 cm d^{-1}, K_{silt} = 61 cm d^{-1}, K_{sand} = 900 cm d^{-1}).

For all five soil types, adding artificial subsurface drainage increases average lateral flows. Hydrographs of each of the five soil types (Figure 4-5) show the change in lateral flow due to subsurface drainage.

A) Silty Clay Loam



B) Loam

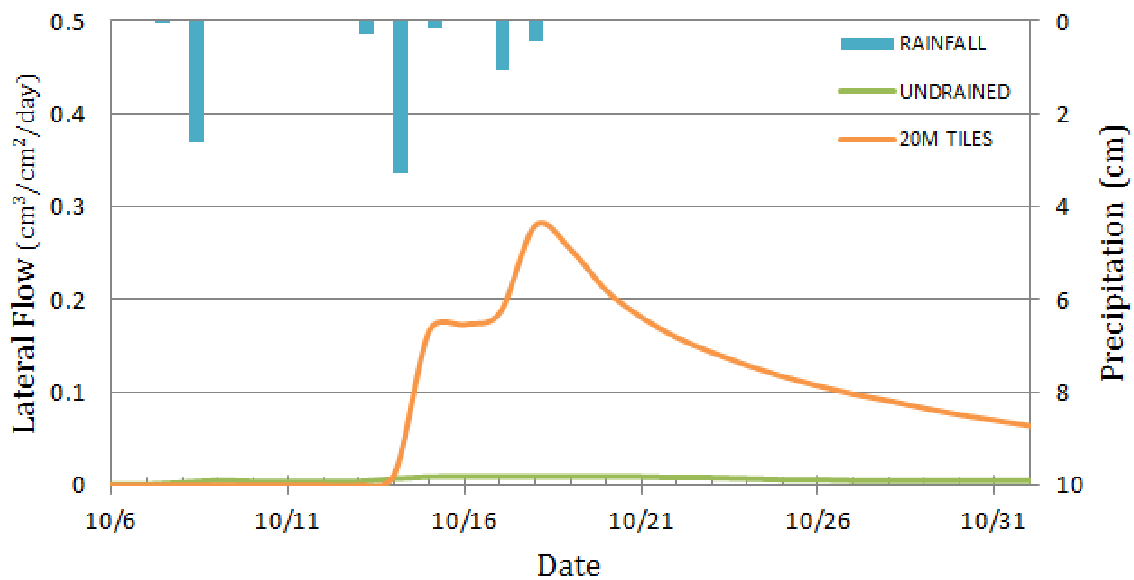
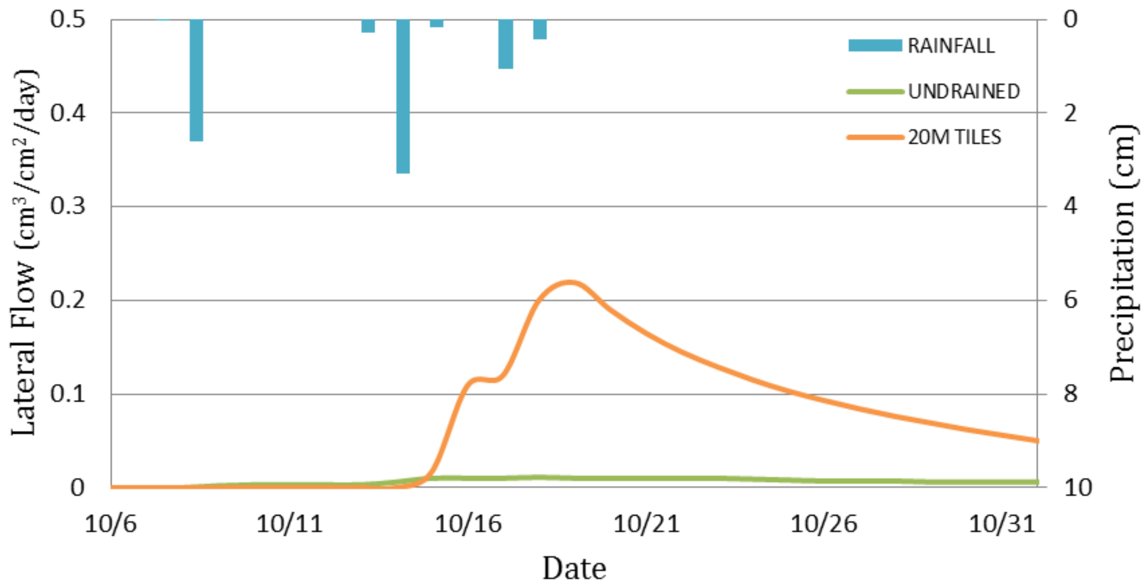


Figure 4-5 Hydrographs of lateral flow of soils A) silty clay loam, B) loam, C) clay, D) silt, and E) sand.

C) Clay



D) Silt

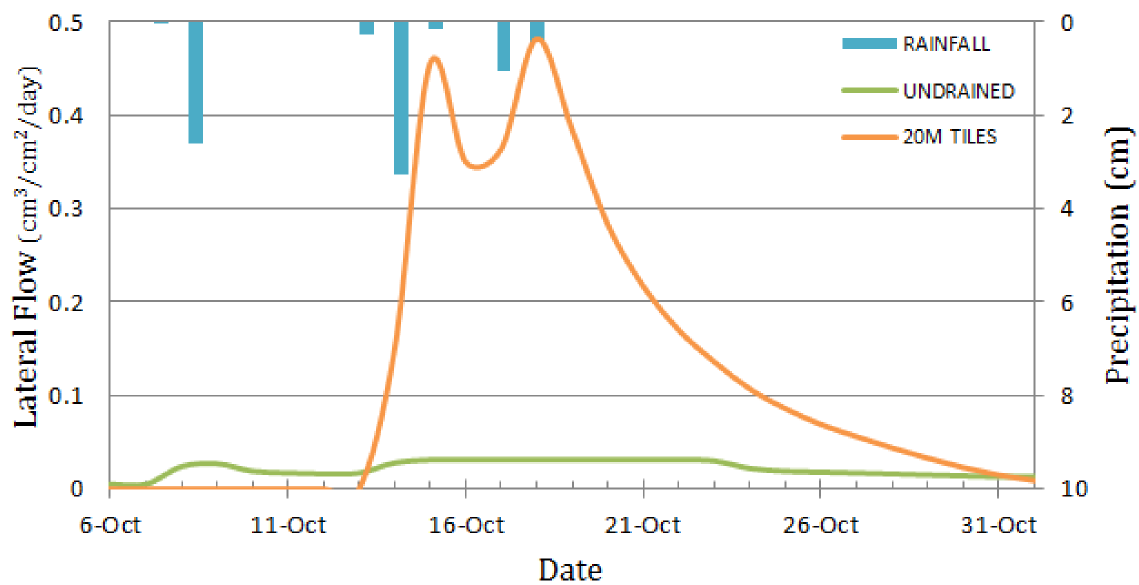


Figure 4-5 Continued.

E) Sand

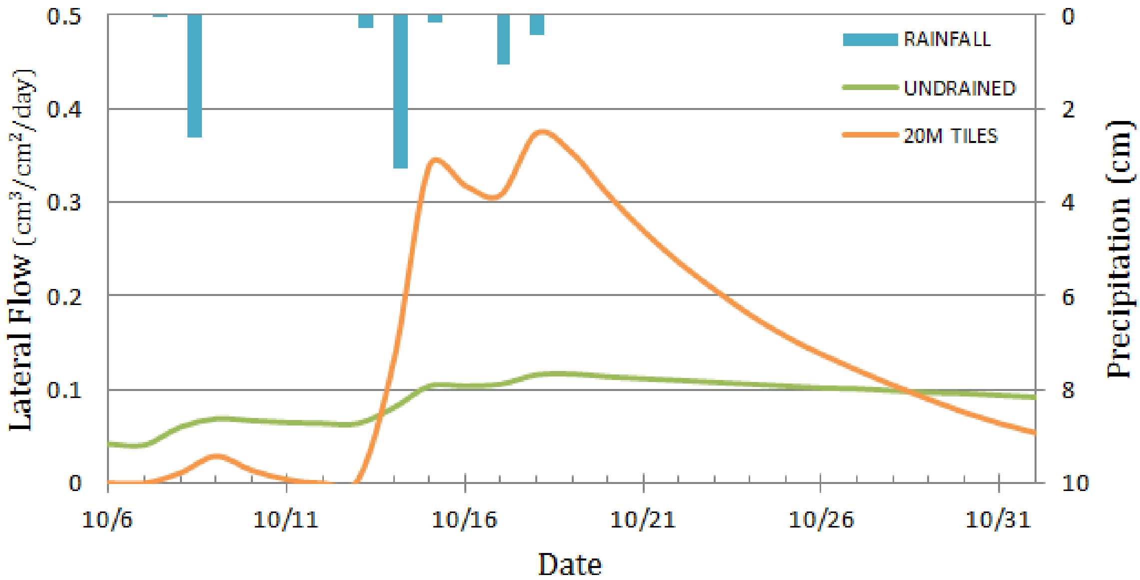


Figure 4-5 Continued.

Figure 4-6 focuses on the annual lateral flows through the subsurface, before and after tile installation, for five different soils. The soil types are arranged in order of ascending hydraulic conductivities. Lateral flows of undrained plots are significantly less than that of drained plots. The annual sum of lateral seepage averaged 1.25 cm for silty clay loam, 1.43 cm for loam, 1.70 cm for clay, 4.04 cm for silt and 30.73 cm for sand soils in the undrained state. The annual sum of lateral drainage averaged 20.66 cm for silty clay loam, 21.30 cm for loam, 21.32 cm for clay, 27.38 for silt, and 33.17 cm for sand soils in plots drained with tiles spaced at 20 m. The effect of soil types on artificial subsurface drainage is effortlessly recognized in Figure 4-6. First, the hydraulic conductivity of the soil defines the lateral flow through the undrained subsurface. Sand has a drastically larger hydraulic conductivity and therefore much larger annual lateral seepage than the other four soil types. Second, after drainage the difference in the lateral flows between sand soils and other soils is dramatically reduced. This occurs because tiling increases the lateral flow for soils with low K, and has minimal impact on soils with high K. Thus, tile drains effectively homogenize the landscape response in terms of annual lateral flow through different soils.

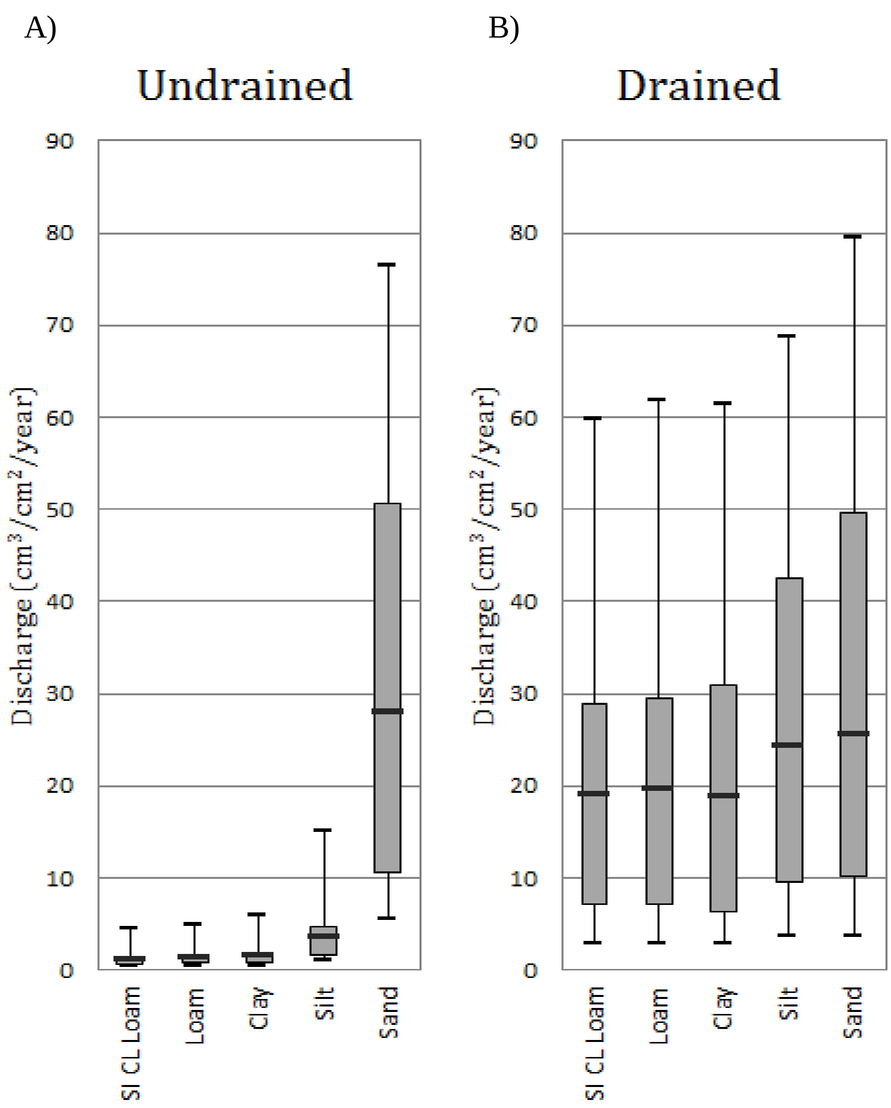


Figure 4-6 Annual sum of lateral flow (presented as discharge normalized by contributing area) through the soil matrix A) before installation of tile drainage and B) after installation of tile drainage. The results are presented in order of increasing hydraulic conductivity and point towards the role of tile drainage in increasing lateral flows as well as homogenizing the landscape ($K_{si\ cl\ loam}$ = 13 cm d^{-1}, K_{loam} = 17 cm d^{-1}, K_{clay} = 21 cm d^{-1}, K_{silt} = 61 cm d^{-1}, K_{sand} = 900 cm d^{-1}).

4.2.2 Effect of subsurface drainage on peak flow attributes as a function of soil type

Figure 4-7 attempts to show the general effect of drainage on peak flows in soil types with low and high hydraulic conductivities. The daily streamflow rate of undrained clay soil is plotted against the daily streamflow rate of a drained (at 20 m spacing) clay soil over 26 years of results (over 9000 data points). The same applies for the second figure but depicts sand soils. The first clear trend to recognize is that the majority of peak flows (between 0 and 5 cm^3 cm^{-2} d^{-1} after drainage is present) are lower flows for clay soils and are higher for sand soils. The other soils with low K act similarly to the clay soils.

A) Clay

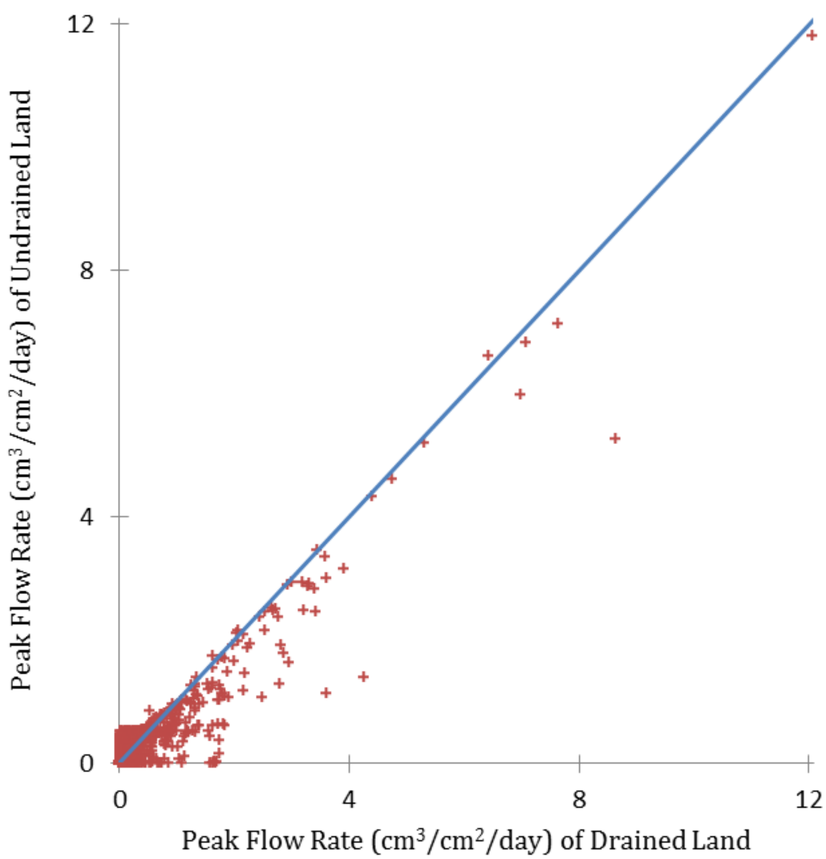


Figure 4-7 Scatterplots of daily peak flow rates of undrained v. drained (at a 20 m spacing) A) clay and B) sand soils from 1987-2012.

B) Sand

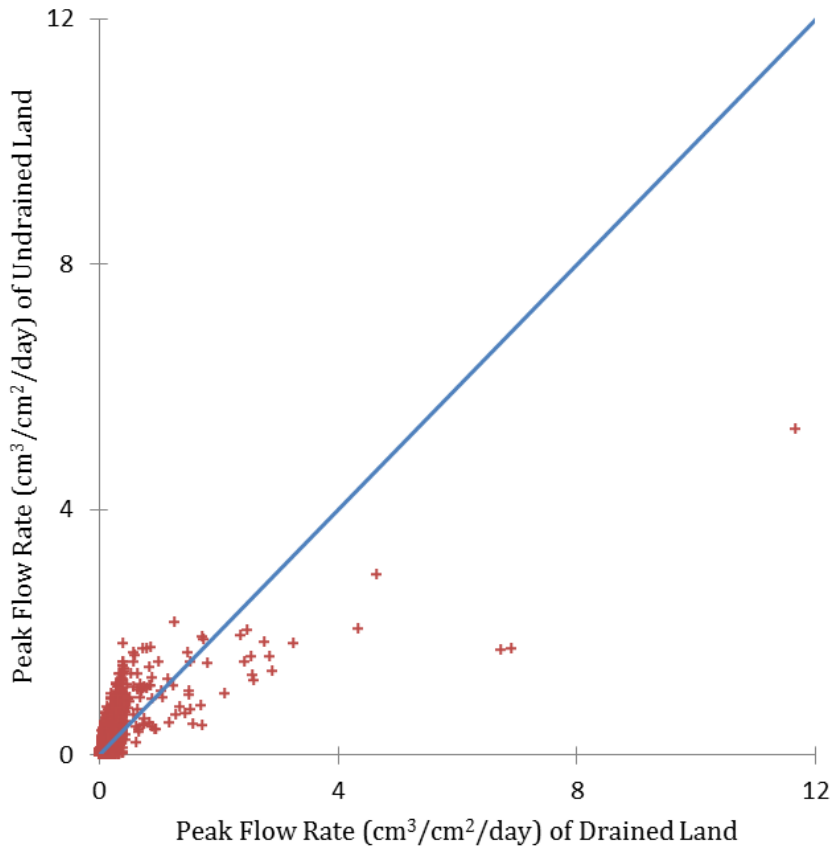
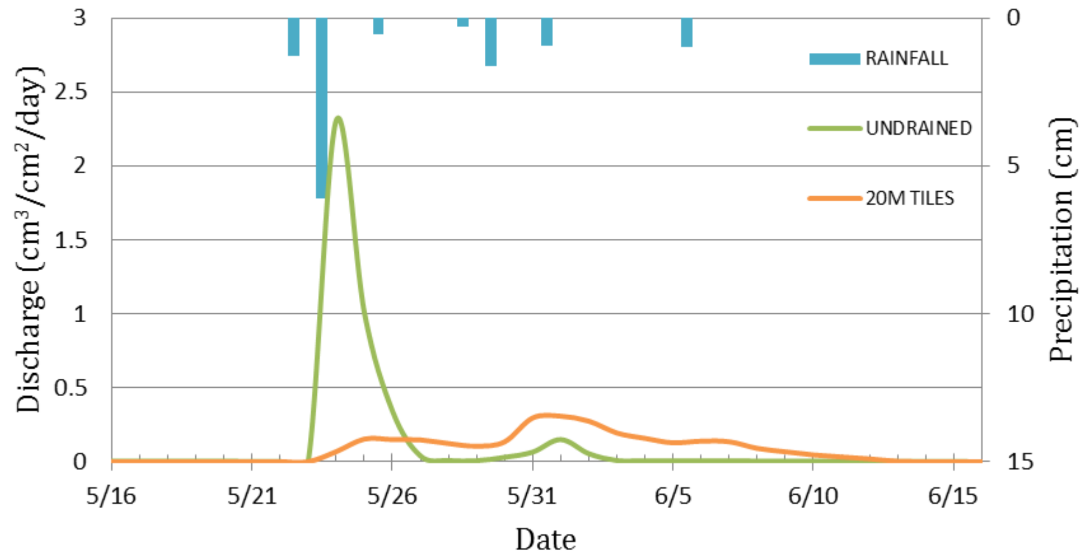


Figure 4-7 Continued.

Though figure 4-7 is beneficial in providing an initial assessment of the changes in peak flows due to additional subsurface drainage, it fails to capture the characteristics of hydrographs during a specific storm event, especially if the peak flow is shifted by a day. Figure 4-8 shows typical streamflow hydrographs during an average spring storm of undrained and drained silty clay loam, loam, clay, silt, and sand soils. After the installation of tile drains (spaced at 20 m), the first large peak of silty clay loam, loam, clay, and silt are decreased, while that of sand is increased. Of the 113 peak flows that exceed 0.05 cm^3 cm^{-2} d^{-1} for clay soils during the 26 years of simulation, 86 (77%) of the peaks were larger before tiles are installed. Conversely, of the 59 peak flows which exceed 0.05 cm^3 cm^{-2} d^{-1} for sand soils in both drained and undrained conditions, 42 (71%) of the peaks are greater in the drained state.

For sand, the groundwater levels of the undrained and drained are similar at the beginning of this storm (at about 1 m below the surface). When the precipitation enters the system, the rainfall quickly infiltrates in sand because of its high hydraulic conductivity. The groundwater level rises and when tiles are present (at 1.06 m below the surface) the water stored in the soil matrix between the surface and the drain tile is quickly removed by the additional subsurface drainage system. The subsurface drainage combines with any surface runoff and causes a higher peak flow. In the undrained state, the water exits slowly by lateral seepage and the groundwater levels typically remain higher in the undrained state. In contrast, the low K of the other soils (silty clay loam, loam, clay, and silt) leads to primarily surface flow in the undrained state. Addition of subsurface drainage helps in infiltration, and thus leads to lower surface runoff, and thus lower peak flow. Since the changes in peak flow show opposite behaviors during the same precipitation events, we can conclude that soil hydraulic conductivities strongly influence the hydrologic response of drained and undrained landscapes.

A) Silty Clay Loam



B) Loam

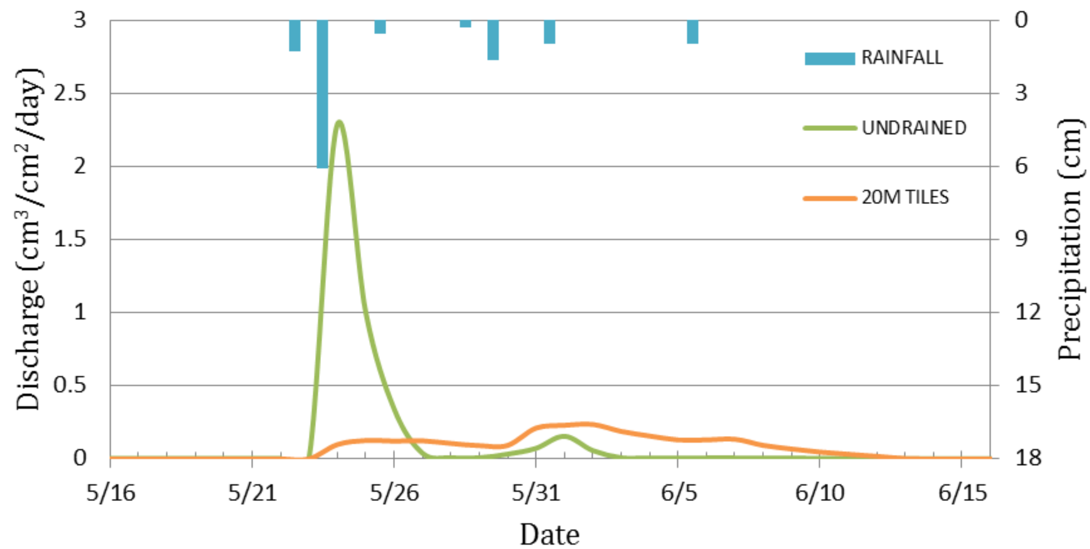
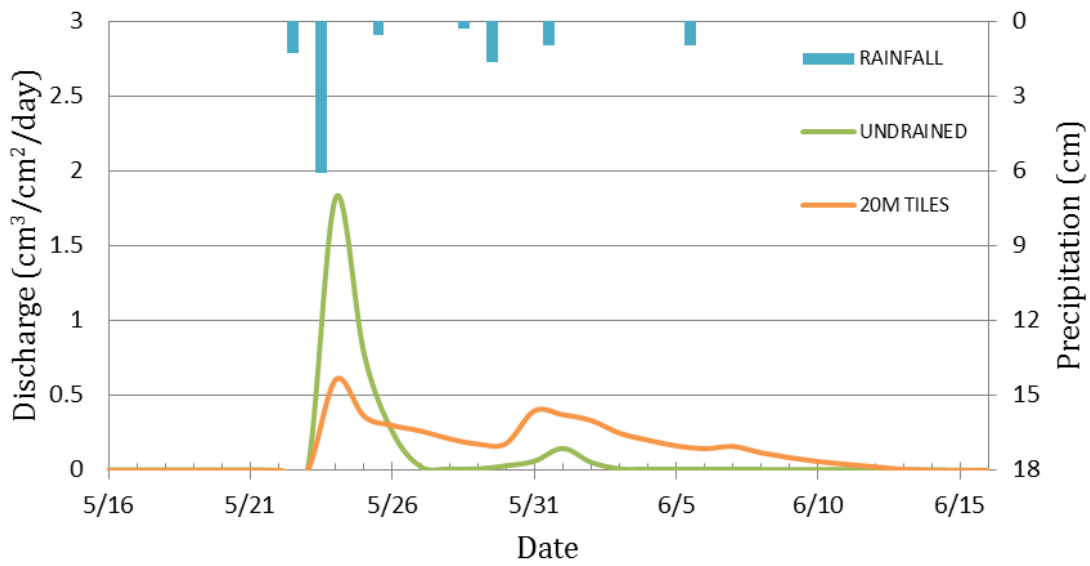


Figure 4-8 Hydrographs during May-June 2007 of A) silty clay loam, B) loam, C) clay, D) silt, and E) sand showing the discharge of stream flow (combination of lateral flow and surface runoff).

C) Clay



D) Silt

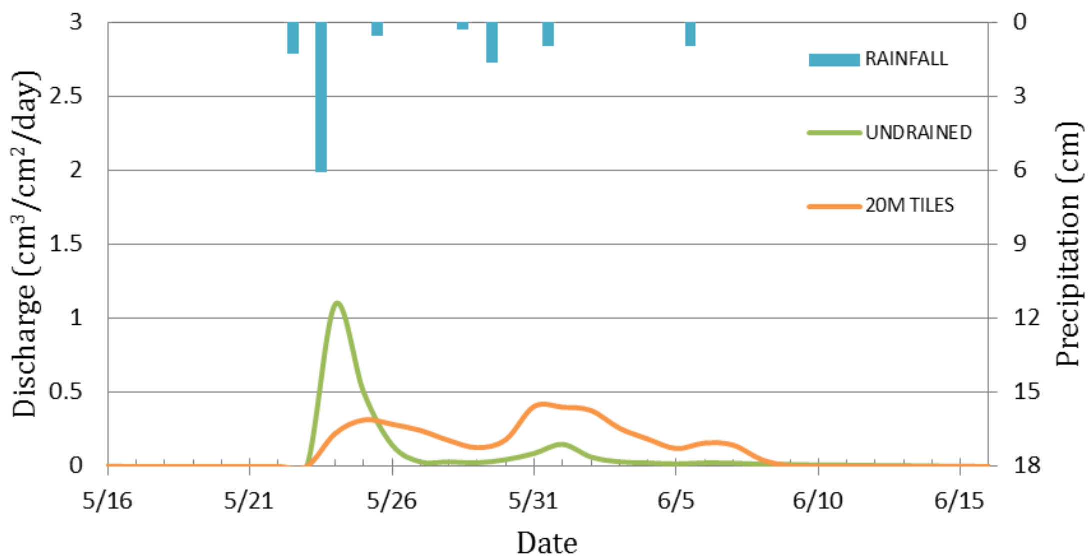


Figure 4-8 Continued.

E) Sand

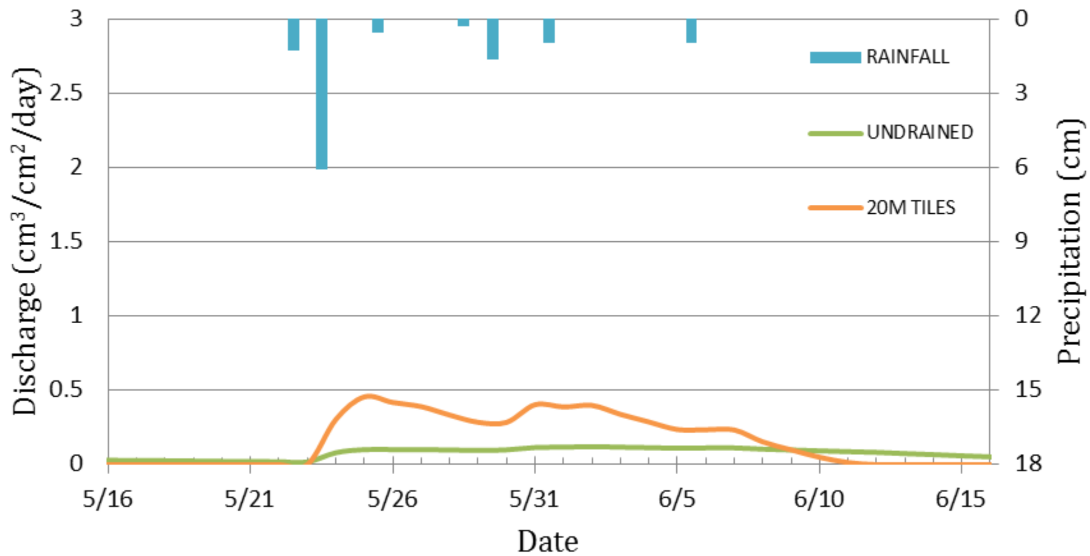


Figure 4-8 Continued.

The maximum peak flows for each of the 26 years in the drained and undrained landscapes are visualized in boxplots in Figure 4-9. The maximum peak flows do not seem to vary before and after installation of tiles. This is usually due to the fact that the largest storm of the year overwhelms the system with precipitation. After the precipitation is infiltrated into the soil matrix and the storage capacity is full, the excess precipitation is rapidly routed out of the soil water regime via surface runoff. The subsurface tiles have a maximum carrying capacity that is negligible compared to the rapid surface runoff during large storm events. Therefore, maximum annual peak flows indicate that little or no change occurs due to additional subsurface drainage.

The maximum annual peak flow metric is limited in its ability to describe the hydrologic response since it is dominated by the largest storm of the year. To overcome this limitation, the Richards-Baker Flashiness Index (FI) that describes the 'flashiness' of the peaks over the entire year was calculated. In the undrained state, the flashiness index is maximum for silty clay loam with the lowest K and minimum for sand with the highest K. A low K indicates slower rates of infiltration into the soil matrix and greater surface runoff, leading to a higher flashiness. Conversely, a high K indicates faster rates of infiltration into the soil matrix and lower surface runoff, leading to a lower flashiness. With tile drainage, the FI of soils with low K decreases due to greater routing of the flow through the subsurface. In contrast, the FI of soils with high K increases due to faster subsurface flow through tiles than through lateral seepage. Thus, flashiness indices of the landscape are homogenized by drainage (Figure 4-10). The flashiness of silty clay loam, loam, clay, and silt soils decreases after 20 m tiles are present while the flashiness of sand increases after tiling. Introducing artificial subsurface drainage systems to the landscape begins to equalize the hydrologic responses of diverse soils.

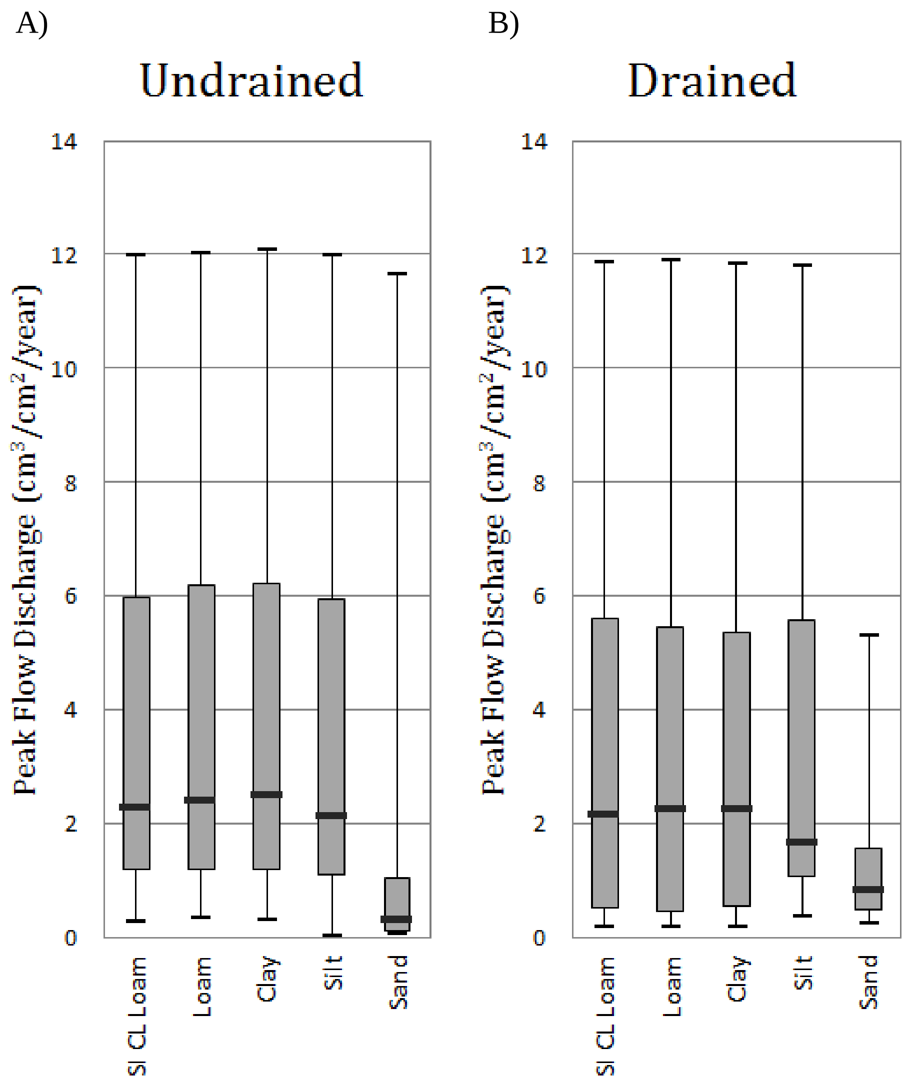


Figure 4-9 Maximum annual peak flow ordinate (presented as discharge normalized by contributing area) for each of the 26 simulated years A) before installation of tile drainage and B) after installation of tile drainage. The results are presented in order of increasing hydraulic conductivity and point towards the role of tile drainage in annual peak flows as well as slightly homogenizing the landscape ($K_{si\ cl\ loam}$ = 13 cm d^{-1}, K_{loam} = 17 cm d^{-1}, K_{clay} = 21 cm d^{-1}, K_{silt} = 61 cm d^{-1}, K_{sand} = 900 cm d^{-1}).

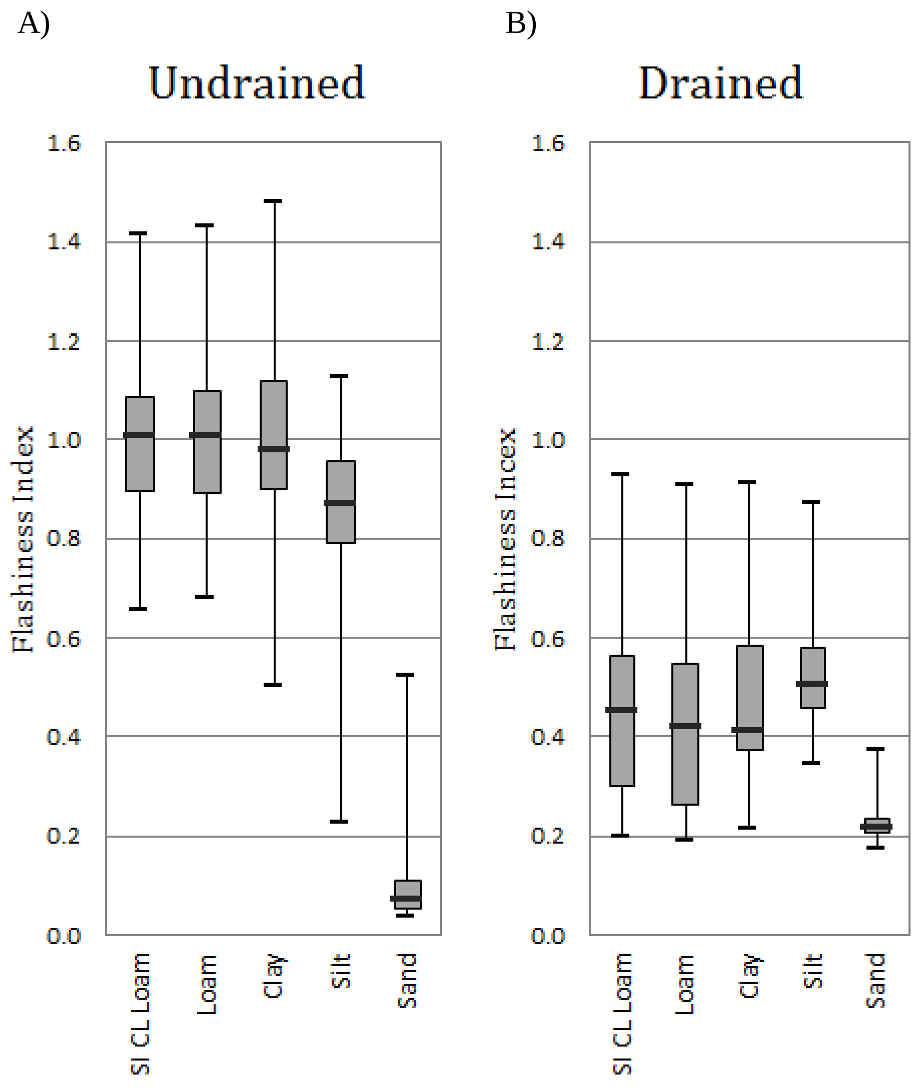


Figure 4-10 R-B Flashiness Index for each of the 26 simulated years A) before installation of tile drainage and B) after installation of tile drainage. The results are presented in order of increasing hydraulic conductivity and point towards the role of tile drainage in the flashiness of a stream as well as homogenizing the landscape ($K_{si\ cl\ loam}$ = 13 cm d^{-1}, K_{loam} = 17 cm d^{-1}, K_{clay} = 21 cm d^{-1}, K_{silt} = 61 cm d^{-1}, K_{sand} = 900 cm d^{-1}).

4.2.3 Effect of subsurface drainage on peak flow attributes as a function of macropore characteristics

To assess the impact of shrinking and cracking on the hydrologic response, the static macropore volume was manipulated along with tile drain spacing in clay soils. The dynamic macropore volume, expressed as a volume fraction, is not constant in time and is used to simulate shrinking and expanding cracks while the static macropore volume is constant in time and is used to simulate macropores that are permanently present in the soil matrix. The static macropore volume consists of structural shrinkage cracks, worm holes, root holes, and pores originating from tillage operations. The static macropore volume is independent of the soil moisture status. The static and dynamic volumes together form the total macropore volume which is distributed over cracks and holes in the horizontal plane according to the structure and geometry of the macropores.

The volume fraction of static macropores as a function of depth is controlled by two input parameters: the volume fraction of static macropores at the soil surface and the depth of the static macropores. By comparing pore volume of large samples with fitted values for θ_{sat} of the original, unmodified Mualem-Van Genuchten functions, the static macropore volume fraction at the soil surface can obtained. In this case, the static macropore volume at the soil surface was varied from 0.02 to 0.32 $cm^3\ cm^{-3}$ (volume per total soil surface volume) where the suggested default value is 0.04 $cm^3\ cm^{-3}$. By increasing the macropore volume at the surface, additional water may enter the macropore domain and the water will be stored until it is infiltrated into the vadose zone or directly into tile drains.

Table 4-3 Flashiness Index showing the relationship between tile drain spacing (m) and the volume of static macropores.

	V = 0.00 (cm^3/cm^3)	V = 0.02 (cm^3/cm^3)	V = 0.04 (cm^3/cm^3)	V = 0.08 (cm^3/cm^3)	V = 0.16 (cm^3/cm^3)	V = 0.32 (cm^3/cm^3)
Undrained	1.01	0.79	0.76	0.66	0.51	0.35
10m tile drains	0.57	0.80	0.78	0.67	0.54	0.37
20m tile drains	0.53	0.80	0.77	0.66	0.53	0.36
30m tile drains	0.55	0.79	0.77	0.68	0.52	0.36

When macropores are present in the simulation, the volume of macropores in drained plots and the flashiness index are directly related (Figure 4-11). Table 4-3 shows the tabulated results of the average annual flashiness index for each scenario. Regardless of the volume of static macropores, when drains are added to a landscape with macropores the flashiness index increases (at most) by only 0.03. As such, drainage density bears little effect on the flashiness index when macropores are simulated. When macropores exist without tile drains the flashiness index is nearly the same as it is with tiles present. Therefore, macropores provide the dominant path for subsurface flow and the influence of subsurface drainage tiles on the daily flashiness of the streamflow is insignificant. Simulating tile drains while disregarding macropores in clay soils shows that the presence of tile drains behaves as if the static macropore volume at the surface is 0.16 cm^3 cm^{-3}. The highest flashiness index results from an absence of both macropores and subsurface drainage systems at a value of 1.01.

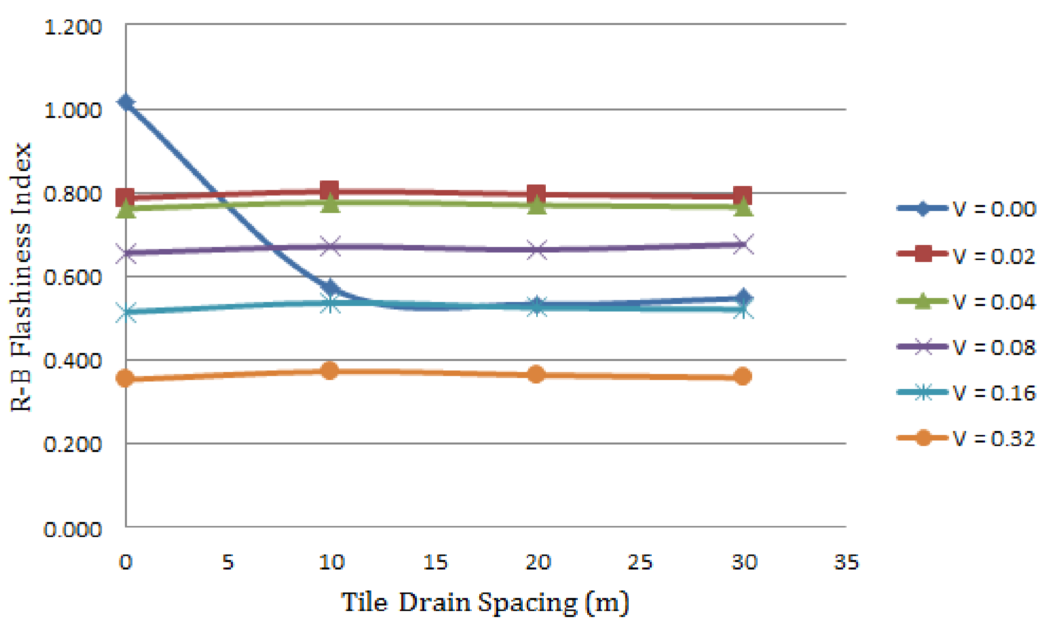
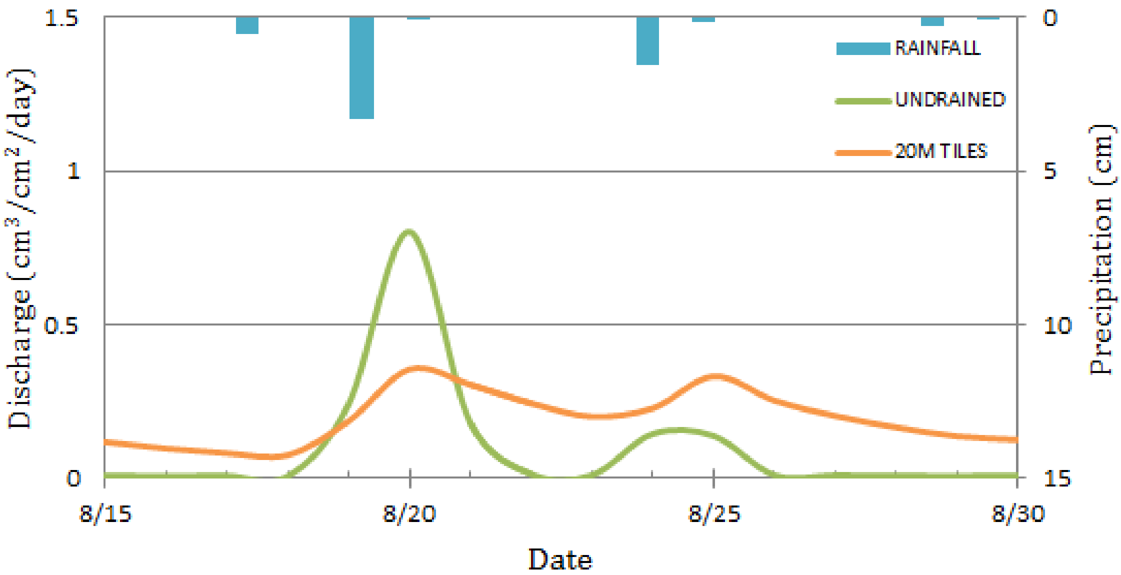


Figure 4-11 R-B Flashiness Index of shrinking and cracking in clayey soils due to macropores.

4.3 Climate Controls on Subsurface Drainage: Rainfall

The other dominant control on hydrologic response is the rainfall regime. Even though peak flows of soils with low hydraulic conductivities are typically decreased after installing subsurface drainage, there are instances when this trend is contradicted. Drained soils with low hydraulic conductivities sometimes produce higher peaks than undrained soils during small precipitation events or during large precipitation events with multiple peaks. Figure 4-12 depicts a hydrograph of clay soils showing such opposite behavior. Due to multiple rainfall events within a relatively short time, peak flows for drained clay soils will be decreased initially and then increased in the following peaks. During the first heavy rainfall event the undrained soil matrix reaches its storage capacity and the precipitation is forced to exit the soil water regime via surface runoff. The second (smaller) rainfall event occurs and is also routed away via surface flow. In the drained condition, the precipitation from the first storm event is almost all infiltrated into the soil matrix where the tile drains regulate the lateral discharge but a small amount of the rainfall forced is forced to leave via surface runoff because the infiltration rate was exceeded. By the time the second rainfall occurs, the soil profile has room to absorb the excess water and exit via tile drains but the new precipitation is combined with the lateral flow from the previous storm, causing a larger peak.

A)



B)

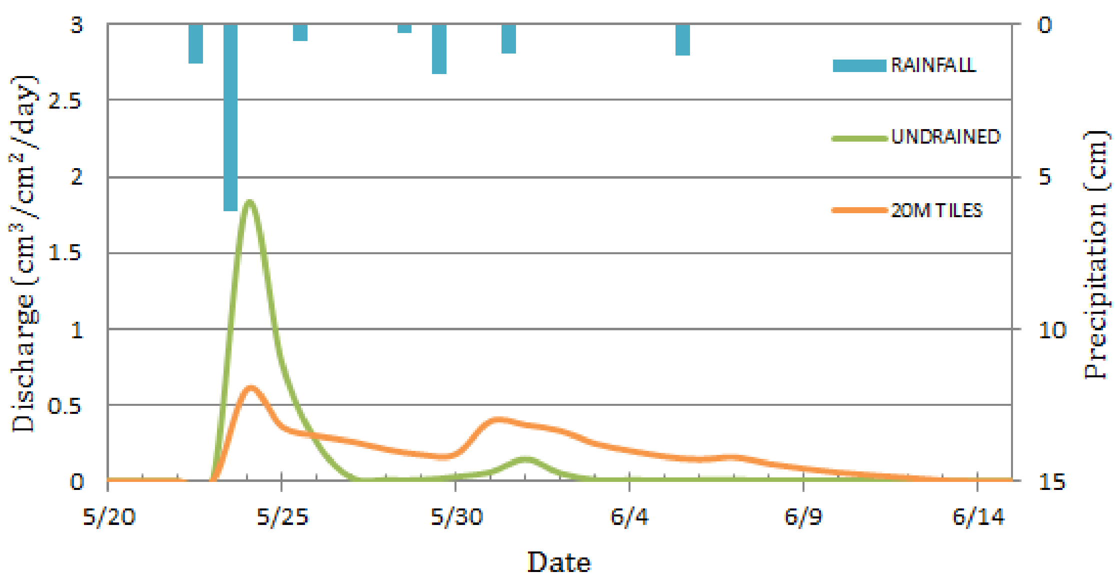


Figure 4-12 Hydrographs of clay soils during average precipitation events for A) August 1990 and B) May-June 2007.

A similar opposing behavior is also observed in soils with high hydraulic conductivities. Peak flows of sand generally increase after installing subsurface drainage but under high rainfall scenarios the peak flow may decrease due to drainage (Figure 4-13). The infiltration rate of sand is naturally high due to its hydraulic conductivity. When intense rainfalls occur in undrained sand landscapes, the precipitation is quickly infiltrated but the soil profile can become fully saturated. Once the storage in the soil matrix is full, the water is forced to exit via surface runoff thereby causing a large peak flow event. In the drained state, the additional drainage through the subsurface pathway keeps the groundwater level lower and leads to a greater amount of the flow to be bypassed through the subsurface leading to a lowering of the peak flow response.

A)

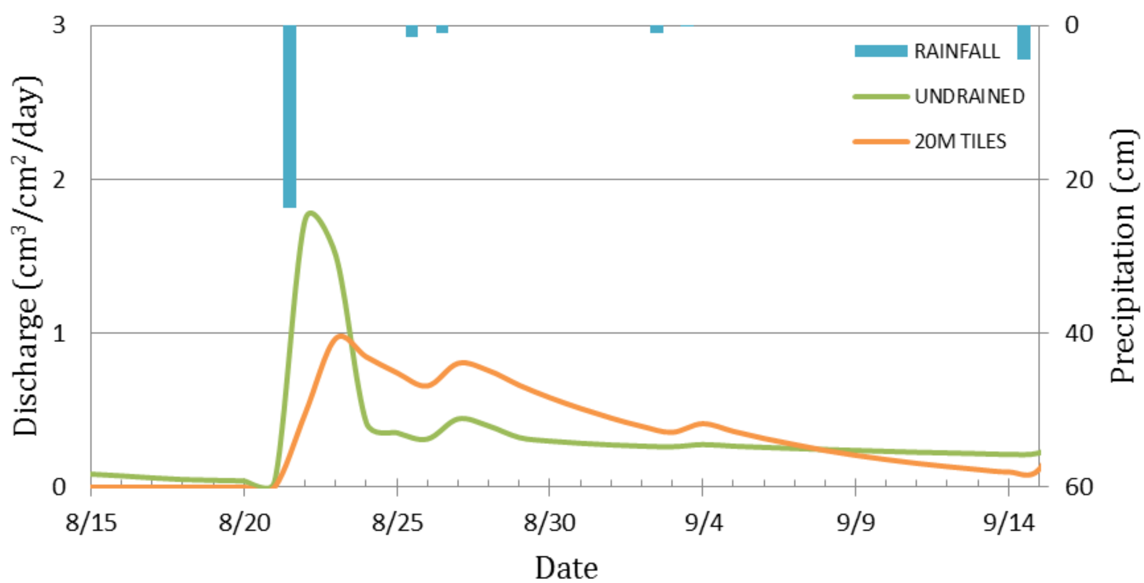


Figure 4-13 Hydrograph of sand soils during a precipitation event in A) August-September 1988 and B) May 1989.

B)

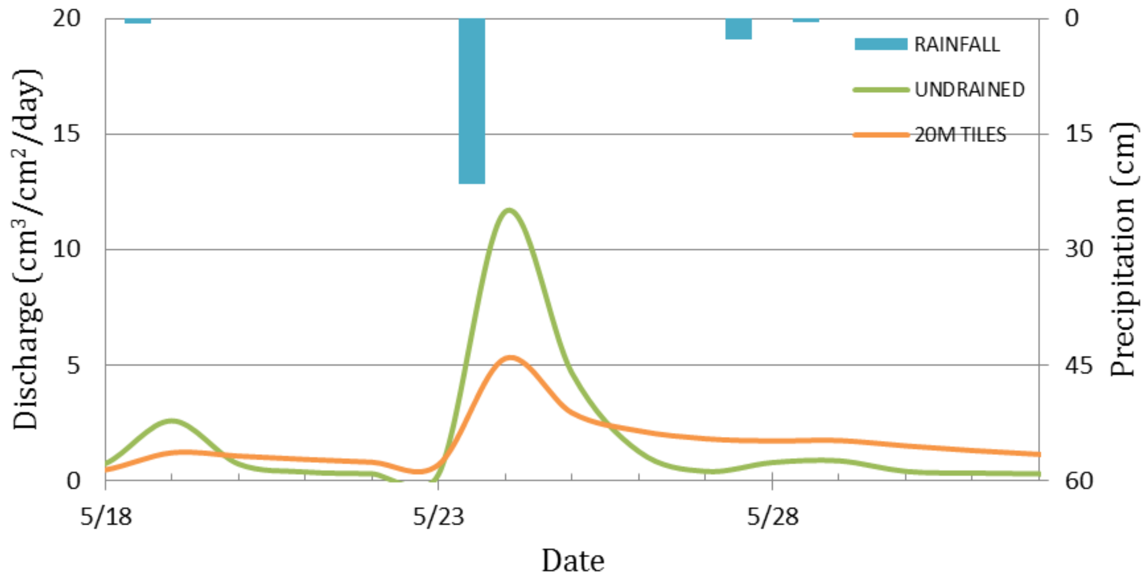


Figure 4-13 Continued.

The maximum peak flows for each of the 26 years in the drained and undrained landscapes are shown again by boxplots in Figure 4-14 but are separated into low, medium, and high rainfall years by calculating the 33th and 66th percentiles since this statistic is used for capturing the distribution of number sets. Eight years range between 132 and 524 mm, nine years range between 525 and 685 mm, nine years range between 686 and 1500 mm of total annual rainfall and make up the three categories: low, medium, and high rainfall regimes. Overall, an increase in the mean annual rainfall leads to an increase in the peak flow for all soils, under both drained and undrained conditions. Consistent with the previous observations, for low and medium rainfall years, the peak flow in sand increases after drainage, but in high rainfall years the peak flow decreases after drainage. However, also as seen before, the peak flows are generally not affected significantly by drainage.

A) Low rainfall regime

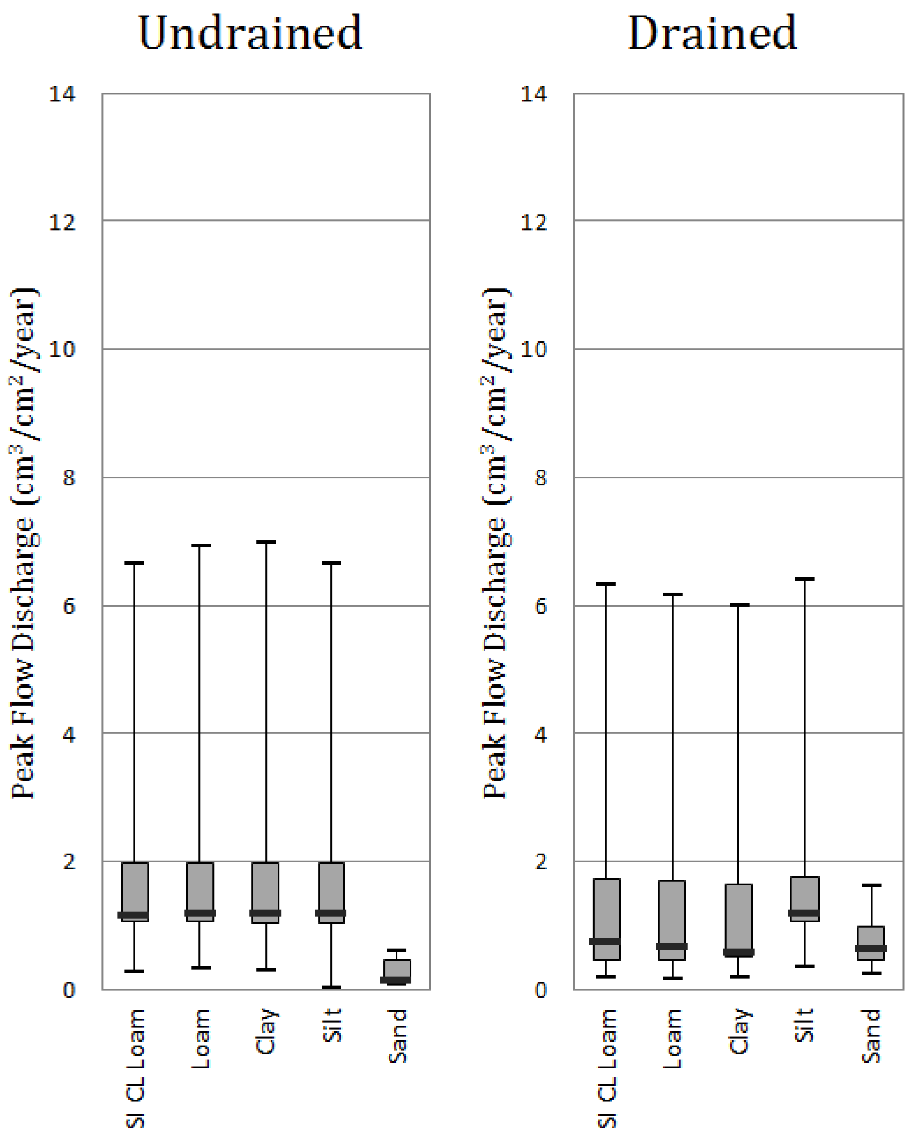


Figure 4-14 Peak flow ordinate for each of the 26 simulated years during A) low, B) medium, and C) high rainfall regimes, in order of hydraulic conductivity ($K_{si\ cl\ loam}$ = 13 cm d^{-1}, K_{loam} = 17 cm d^{-1}, K_{clay} = 21 cm d^{-1}, K_{silt} = 61 cm d^{-1}, K_{sand} = 900 cm d^{-1}) before and after drainage.

B) Medium rainfall regime

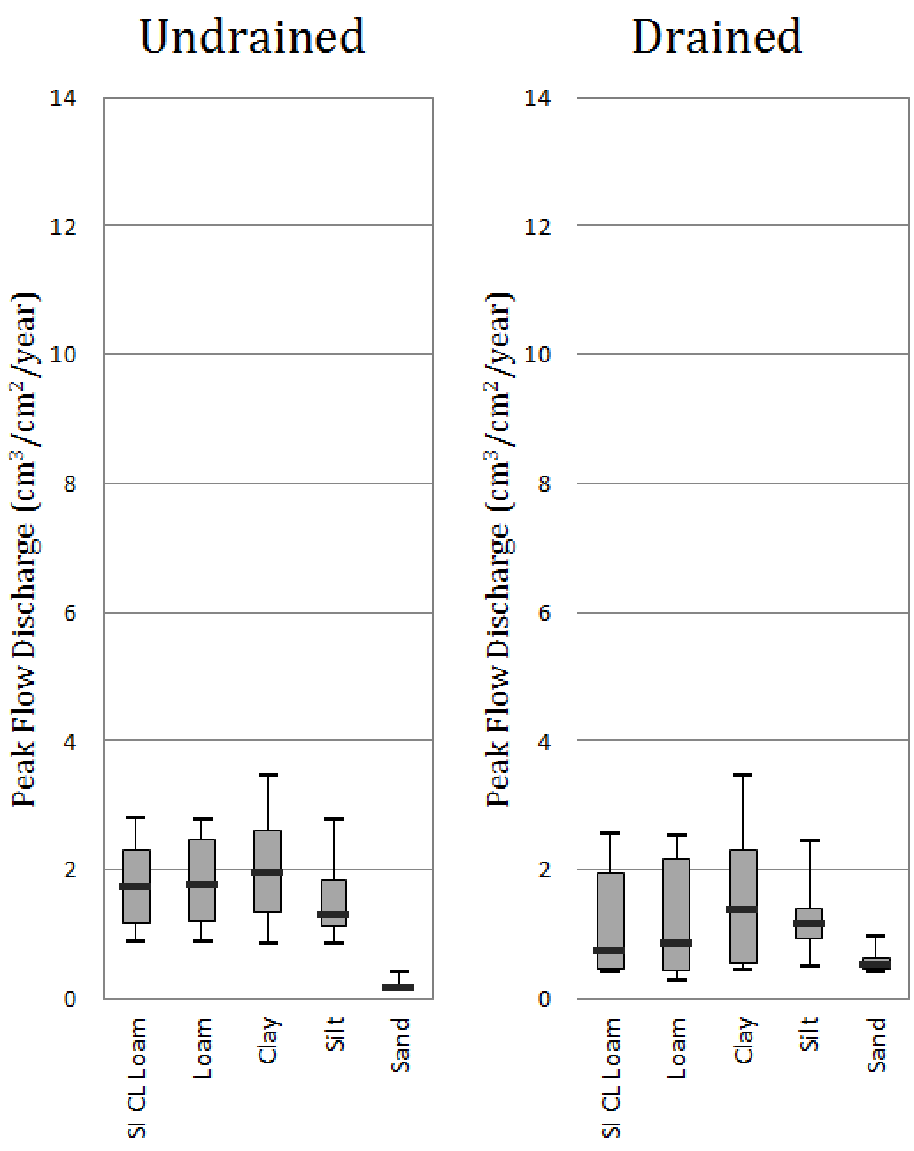


Figure 4-14 Continued.

C) High rainfall regime

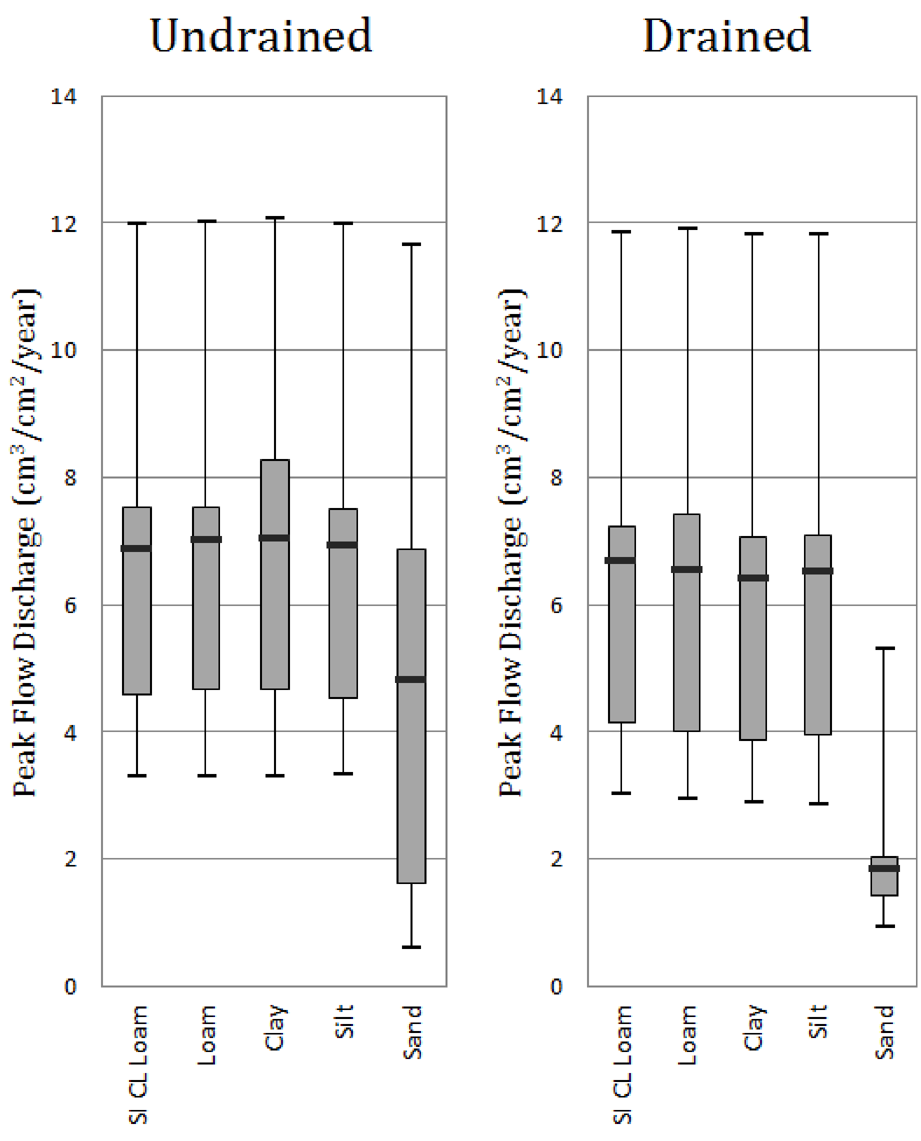


Figure 4-14 Continued.

We thus investigated the results with the Richards-Baker Flashiness Index, separated by low, medium, and high rainfall years and plotted in Figure 4-15. Again, though the maximum peak flows of all soils remain relatively similar before and after drainage, flashiness indices show a greater response to drainage. Though the flashiness indices of silty clay loam, loam, clay, and silt soils consistently decrease after 20 m tiles are present, the rainfall regime impacts the magnitude of the flashiness indices. As the annual sum of rainfall increases, the flashiness index increases for soils with low hydraulic conductivities. This remains true both before and after drainage. Once sand is drained, the rainfall regime has little impact on the flashiness index. After drainage the streamflow is completely dominated by lateral flow and surface runoff is minimal. The drainage tiles reach a maximum carrying capacity during intense storm events and therefore regulate the amount of lateral flow and mitigate the flashiness index whether the rainfall is high or low.

A) Low rainfall regime

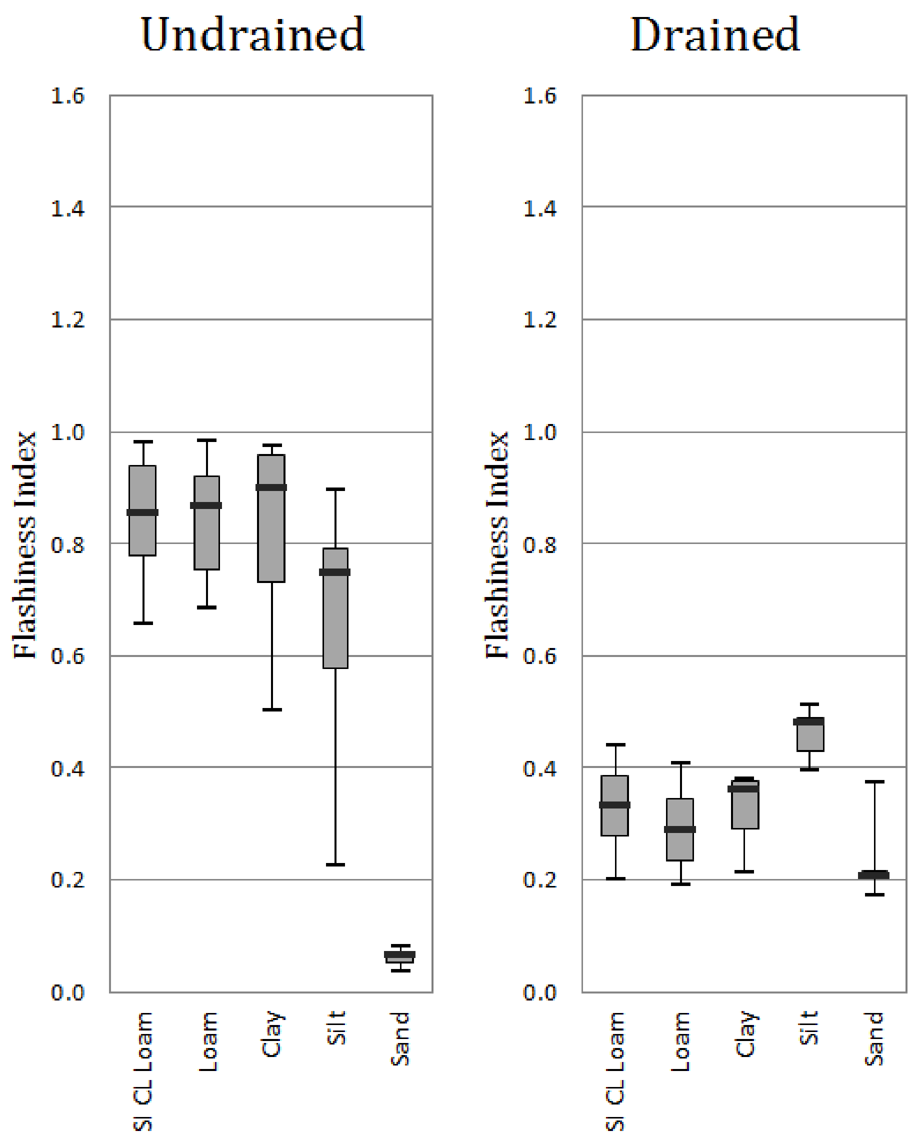


Figure 4-15 Flashiness Index for each of the 26 simulated years during A) low, B) medium, and C) high rainfall regimes, in order of hydraulic conductivity ($K_{si\ cl\ loam}$ = 13 cm d^{-1}, K_{loam} = 17 cm d^{-1}, K_{clay} = 21 cm d^{-1}, K_{silt} = 61 cm d^{-1}, K_{sand} = 900 cm d^{-1}) before and after drainage.

B) Medium rainfall regime

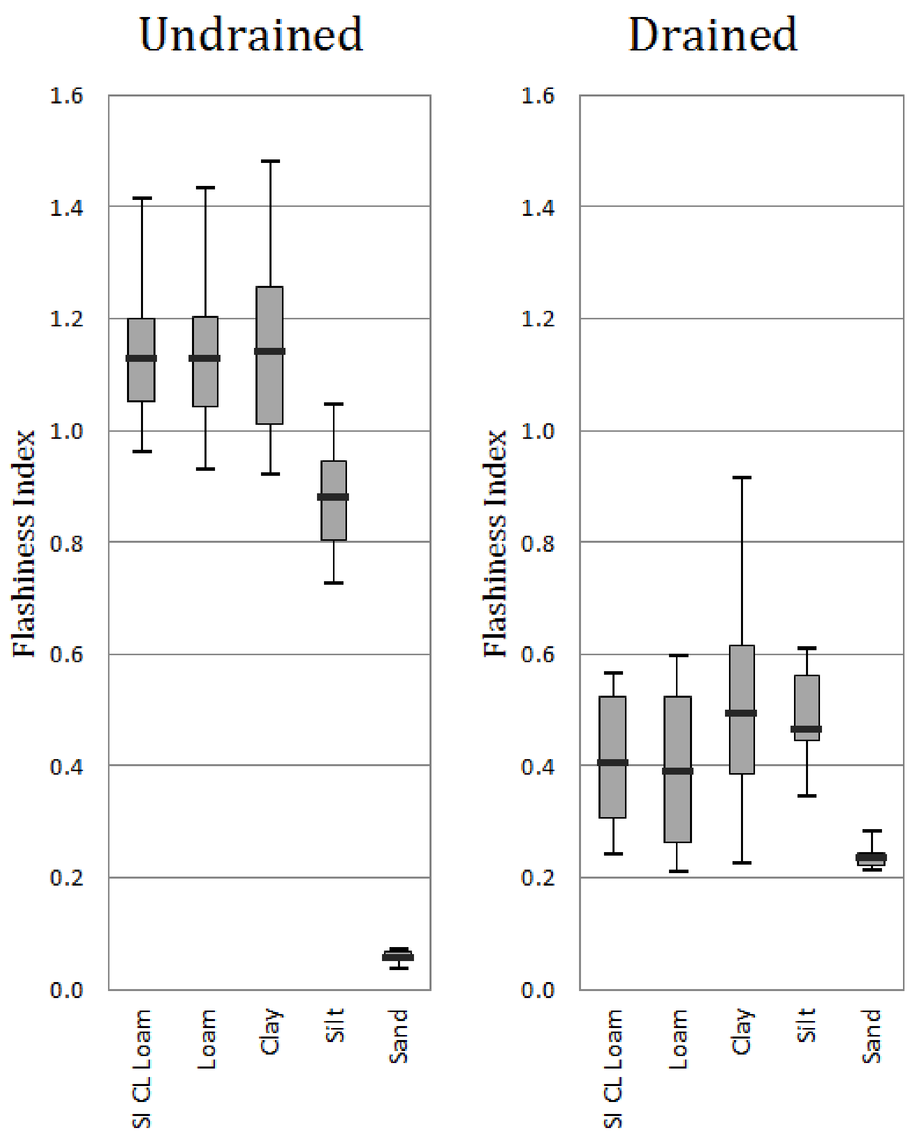


Figure 4-15 Continued.

C) High rainfall regime

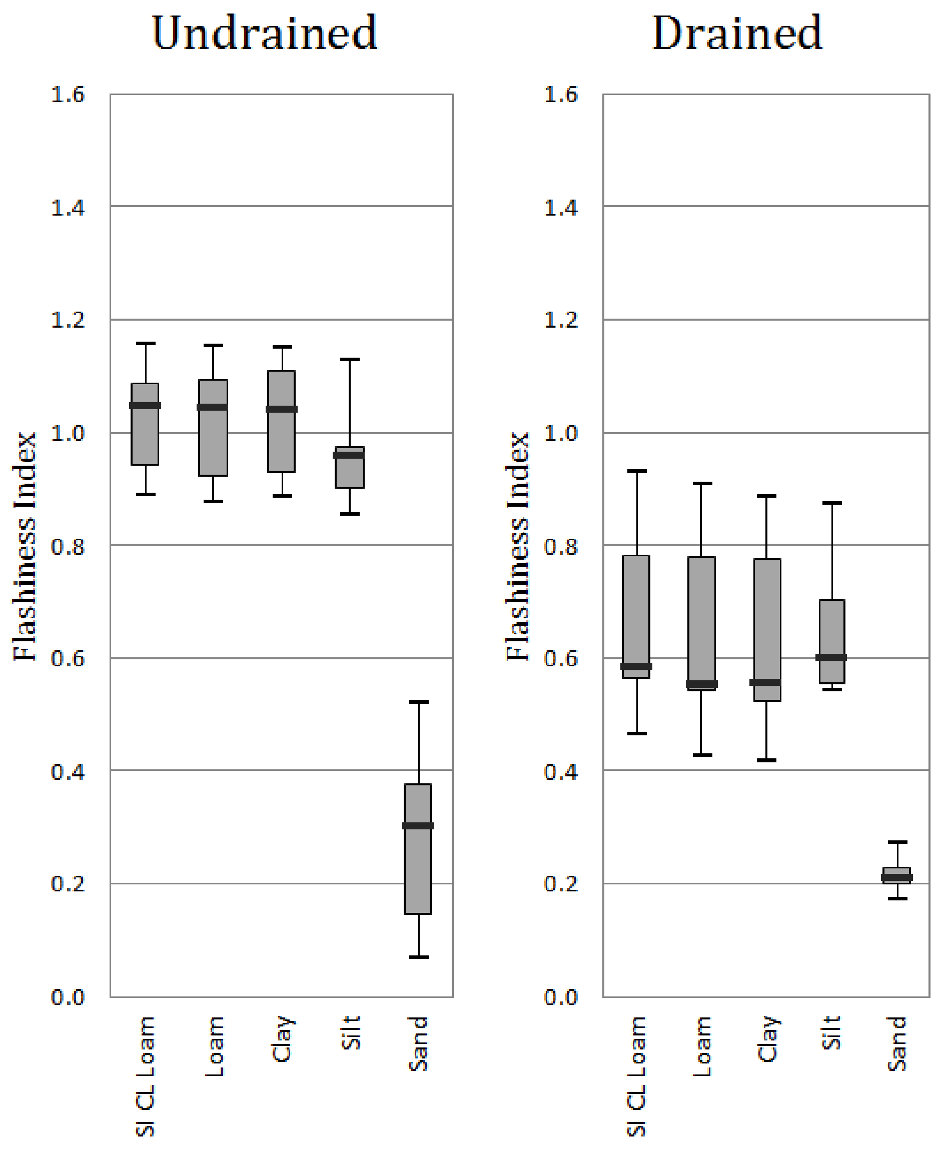


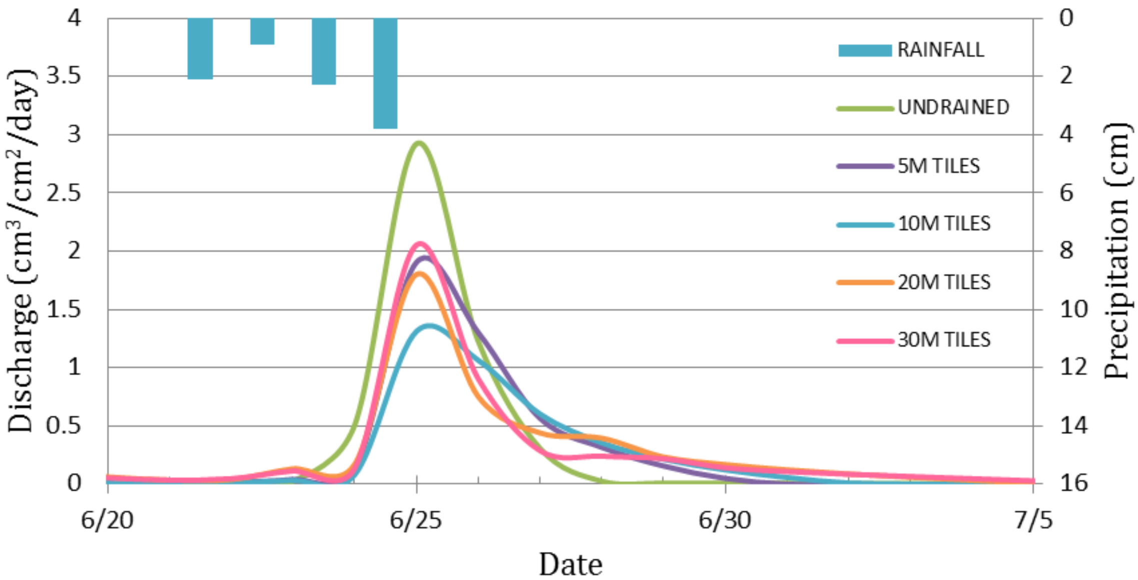
Figure 4-15 Continued.

4.4 Anthropogenic Controls on Subsurface Drainage: Drainage Spacing

Finally, we explored the role of anthropogenic controls on modifying the subsurface drainage. Until this point in the simulations, all landscapes have been drained by tile drains spaced 20 m apart. In the agriculture industry, tile drains are installed at various spacings for many reasons: closer spaces to mitigate water-logging of the soil, larger spaces to meet cost constraints, specific spaces to increase a particular crop yield, etc. By altering the distance between adjacent parallel tile drains, various anthropogenic controls are investigated by discovering specific hydrologic responses and recognizing trends.

Figures 4-16 and 4-17 show the hydrographs of loam and clay soils, respectively, at various tile spacings. The peak flows for loam soils are lowest when tiles are spaced at 10 m and then 20 m and increase when the tiles are dense or sparse. The peak flows of clay soils show similar behaviors. When the tiles are dense, the lateral drainage during a storm event combines with runoff because the tiles are conveying water at a rapid rate. When tiles are spread further apart, the soil surface becomes saturated quickly and the surface runoff dominates the discharge because the lateral drainage transports water at a slower rate. This suggests that peak flows in landscapes with low hydraulic conductivities can be mitigated by ideal subsurface drainage design.

A)



B)

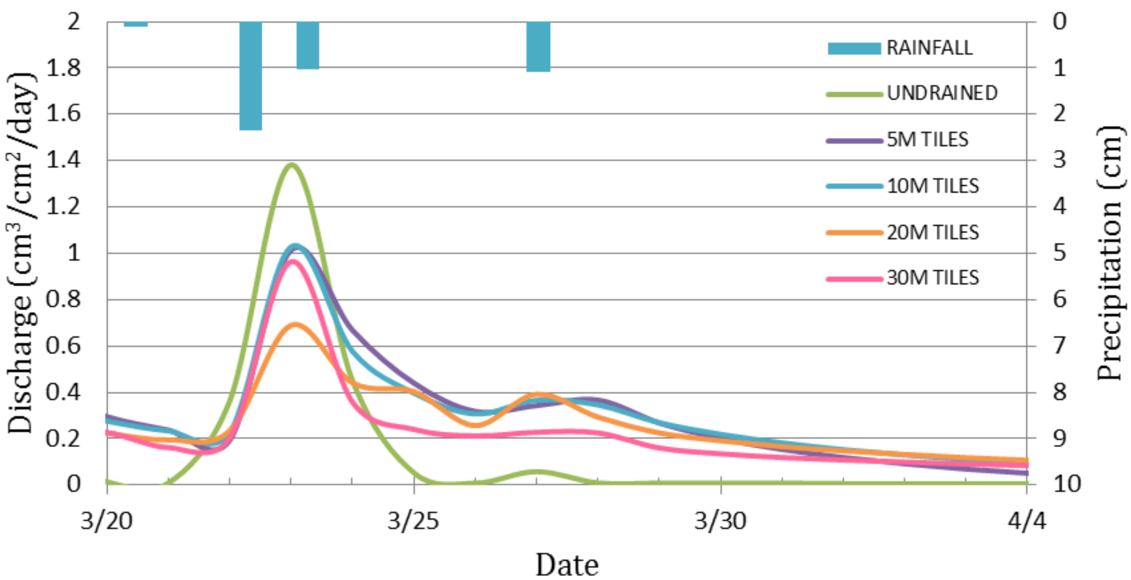
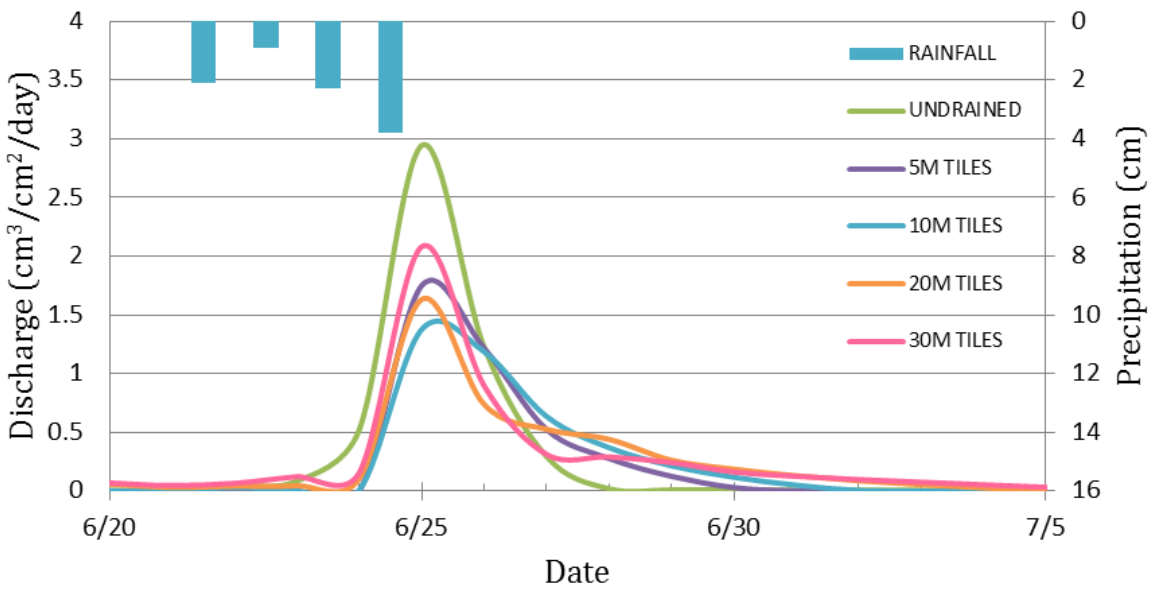


Figure 4-16 Hydrograph of loam soils during a precipitation event in A) June 1989 and B) March 1991.

A)



B)

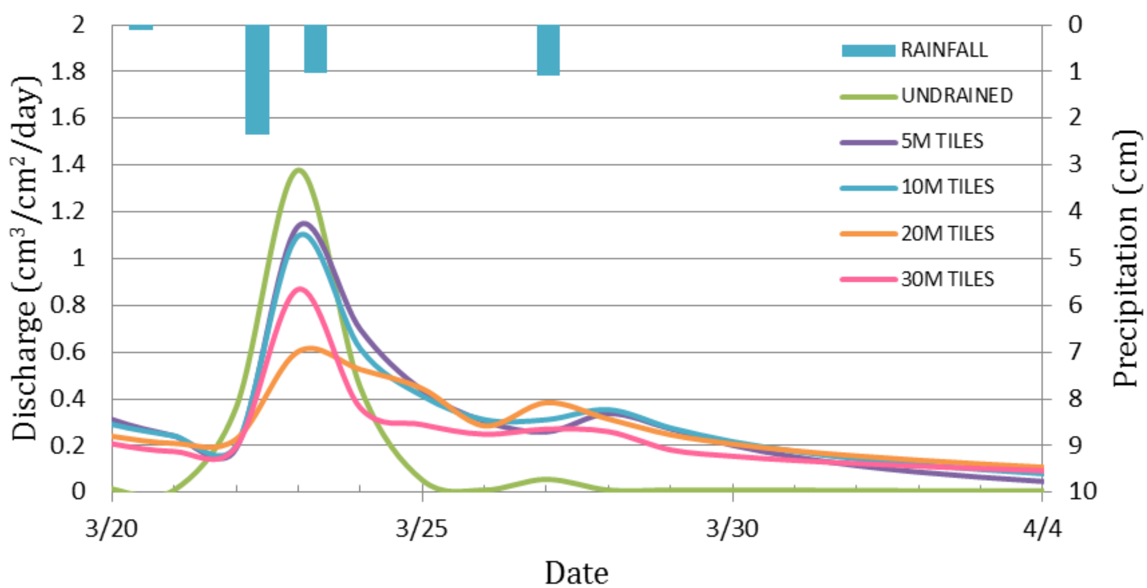


Figure 4-17 Hydrograph of clay soils during a precipitation event in A) June 1989 and B) March 1991.

By plotting the various distances between tile drains and the resulting flashiness indices of one year, clear patterns are recognized (Figure 4-18). The saddle shape of the soils with lower hydraulic conductivities suggests that for each soil type there is an ideal distance between tile drains to mitigate the flashiness of the hydrologic response. The optimum drain spacing can be found at the lowest point of the curve where the flashiness index is at a minimum. Since clay and loam have comparable hydraulic conductivities (20.7 and 16.9 cm d^{-1} respectively) they are expected to behave similarly. The flashiness indices of sand and silt soils appear to decrease as distance between tiles increases but will also show a saddle shape when tiles are spaced further apart. This is because at some distance of tile spacing, the effect of drainage would disappear or be miniscule at best and the landscape will behave as undrained.

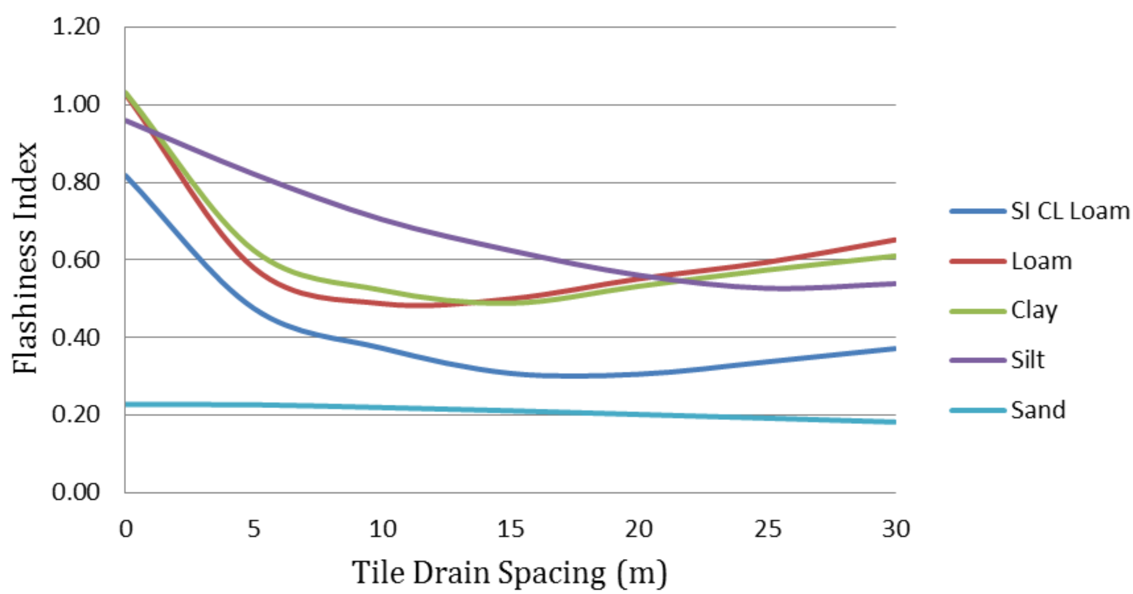


Figure 4-18 R-B Flashiness Index of soils during 2008 (a high precipitation year) varying distance between tile drains with “0” referring to the undrained state.

4.5 Interplay of Climate, Landscape and Anthropogenic Controls on Subsurface Drainage

It is well known that rainfall, soil textures, and tile drains all play a role in the hydrologic response of a landscape. To best understand the mixture of these key factors on the hydrology, the results of the flashiness index were separated into low, medium, and high rainfall years; 5, 10, 15, 20, 25, and 30 meter distances between tiles; and soil types of silty loam clay, loam, clay, silt, and sand (Table 4-4). In Table 4-4, the lowest flashiness index values are in bold. These values show the optimal drain spacing for soil types during different rainfall regimes if the goal is to reduce flashiness of streamflow. The Iowa Drainage Guide (CES, 2012) suggests similar results for these soil types and provides validity to our results. The drainage guide, however, describes tile spacing by soil types specific to Iowa and not by broad categories as investigated in this study.

The flashiness index and the distance between tile drains for each of the 26 years is plotted and then separated into low, medium, and high rainfall years. Figure 4-19 shows one representative year from each of the three rainfall regime categories. For soils with the lowest hydraulic conductivities (silty clay loam, clay, and loam), high rainfall years show a strong saddle shape behavior with a minimum flashiness at around 15 m between tile drains. The medium rainfall years also show a saddle shape for these soils, but the 'dip' is shifted slightly to the right at around 20 to 25 m. Low rainfall years however, exhibit a monotonic decrease in flashiness with increase in drain spacing. The saddle shaped behavior is not evident in silt soils with a slightly higher K. These soils exhibit a monotonic decrease in flashiness as distance between tiles increases, though they tend to level off around 25 and 30 m spacing, especially during years with higher rainfall. This figure also strengthens the conclusion that subsurface drainage decreases the flashiness index of soils with low hydraulic conductivities regardless of rainfall characteristics.

It is important to note that sand is the only soil which shows an increase of flashiness due to subsurface drainage. The low and medium rainfall years presented in Figure 4-19 show an increase of flashiness due to drainage while the high rainfall years show little change of flashiness after tiles are installed. These results show one year that characterizes each of the rainfall regimes: low, medium, and high. These conclusions strengthen the expectations from the boxplots in Figure 4-15.

Table 4-4 Flashiness Index data for each of the four soil types, averaged by low, medium, and high rainfall years and overall. The lowest FI values are in bold.

SILTY CLAY LOAM (K = 13 cm/d)							
Average Flashiness Index	Undrained	5m	10m	15m	20m	25m	30m
Low rainfall years	0.82	0.48	0.37	0.31	**0.31**	0.34	0.37
Medium rainfall years	1.11	0.56	0.46	0.40	**0.39**	0.40	0.44
High rainfall years	1.02	0.70	**0.62**	0.63	0.66	0.70	0.74
All years	1.01	0.59	0.49	**0.46**	0.47	0.49	0.53

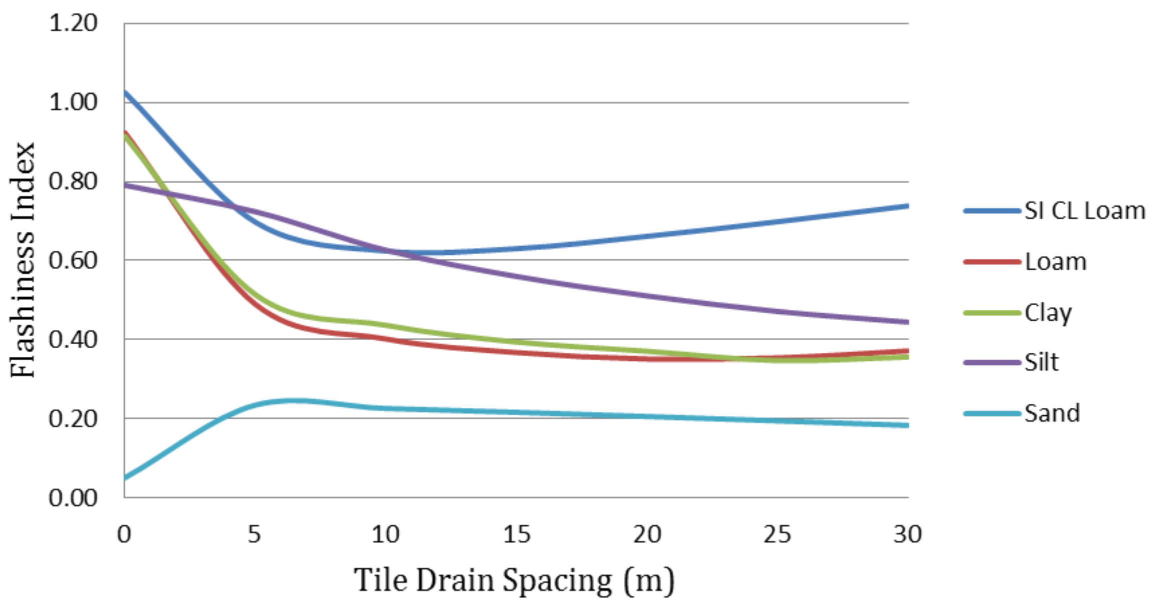
LOAM (K = 17 cm/d)							
Average Flashiness Index	Undrained	5m	10m	15m	20m	25m	30m
Low rainfall years	0.81	0.44	0.35	0.29	**0.27**	0.29	0.33
Medium rainfall years	1.11	0.53	0.45	0.39	**0.37**	0.37	0.41
High rainfall years	1.02	0.67	0.61	**0.61**	0.64	0.67	0.72
All years	1.00	0.56	0.48	0.44	**0.44**	0.46	0.50

CLAY (K = 21 cm/d)							
Average Flashiness Index	Undrained	5m	10m	15m	20m	25m	30m
Low rainfall years	0.79	0.46	0.39	0.35	0.32	**0.29**	0.31
Medium rainfall years	1.12	0.60	0.53	0.50	0.48	**0.47**	0.47
High rainfall years	1.02	0.70	0.64	**0.61**	0.63	0.66	0.69
All years	1.00	0.60	0.53	0.50	**0.49**	0.49	0.51

SILT (K = 61 cm/d)							
Average Flashiness Index	Undrained	5m	10m	15m	20m	25m	30m
Low rainfall years	0.61	0.66	0.57	0.51	0.46	0.41	**0.37**
Medium rainfall years	0.85	0.72	0.61	0.53	0.47	0.42	**0.39**
High rainfall years	0.96	0.84	0.74	0.68	0.65	0.63	**0.62**
All years	0.83	0.75	0.65	0.58	0.53	0.49	**0.47**

SAND (K = 900 cm/d)							
Average Flashiness Index	Undrained	5m	10m	15m	20m	25m	30m
Low rainfall years	**0.06**	0.27	0.26	0.25	0.24	0.23	0.22
Medium rainfall years	**0.06**	0.26	0.25	0.24	0.23	0.22	0.21
High rainfall years	**0.28**	0.24	0.23	0.22	0.22	0.21	0.20
All years	**0.13**	0.25	0.25	0.24	0.23	0.22	0.21

A) Low rainfall regime



B) Medium rainfall regime

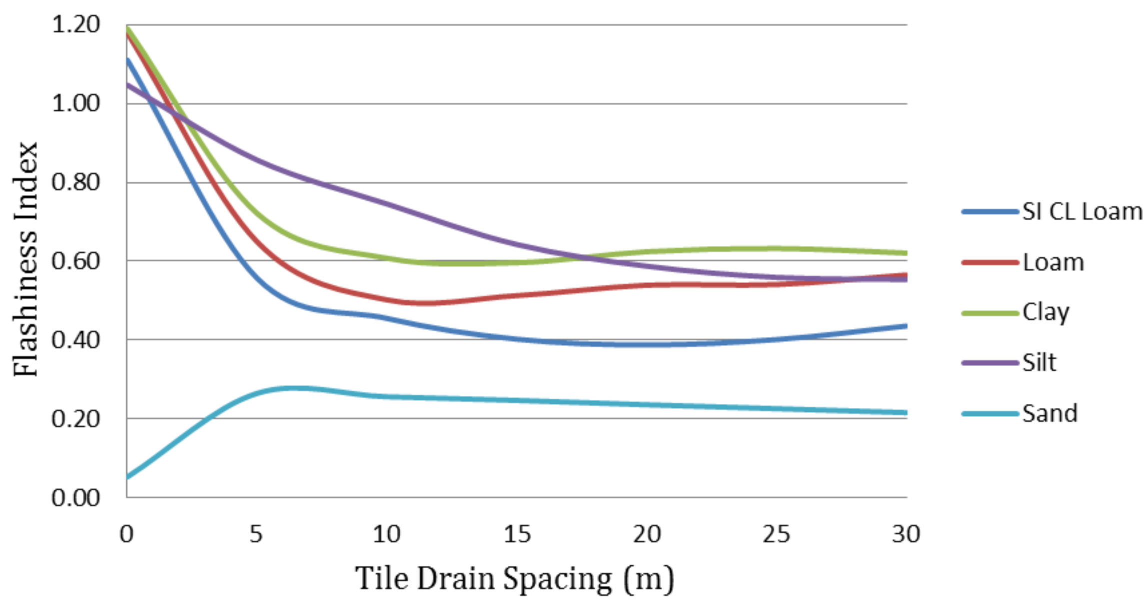


Figure 4-19 R-B Flashiness Index of soils during A) low (2012), B) medium (1999), and C) high (2008) rainfall regimes of four different soils with varying distance between tile drains with “0” referring to the undrained state.

C) High rainfall regime

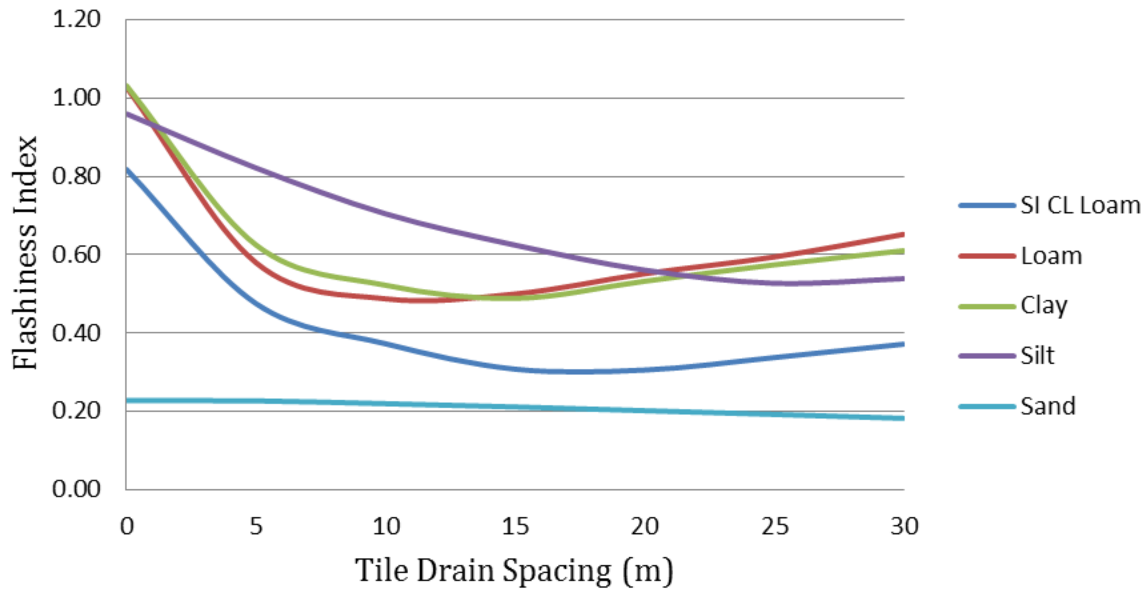


Figure 4-19 Continued.

To understand the role of soil type better, we plotted the percent decrease in flashiness due to tile drains (drained flashiness divided by the undrained flashiness) against the distance between drains (Figure 4-20). For silty clay loam, loam, clay, and silt, the average drained flashiness is less than the average undrained flashiness independent of tile spacing. For sand soils, the undrained flashiness is lower than the drained counterpart. Since sand has a high hydraulic conductivity, when the tiles are more dense, flashiness is increased. Loam and clay soils show only a slight variation due to change in tile management practices, but they still behave as expected with a saddle shaped curve. The optimum drain spacing is 20 m for both soil types when the flashiness is decreased by 56% for loam and 51% for clay. Of these five soils, silt and sand are more sensitive to the spacing of tile drains as the change in discharge is dependent on the distance between the tiles. This plot also strengthens the conclusion that over 26 years of various precipitation regimes, discharge from sandy soils is flashier after tile drains are installed.

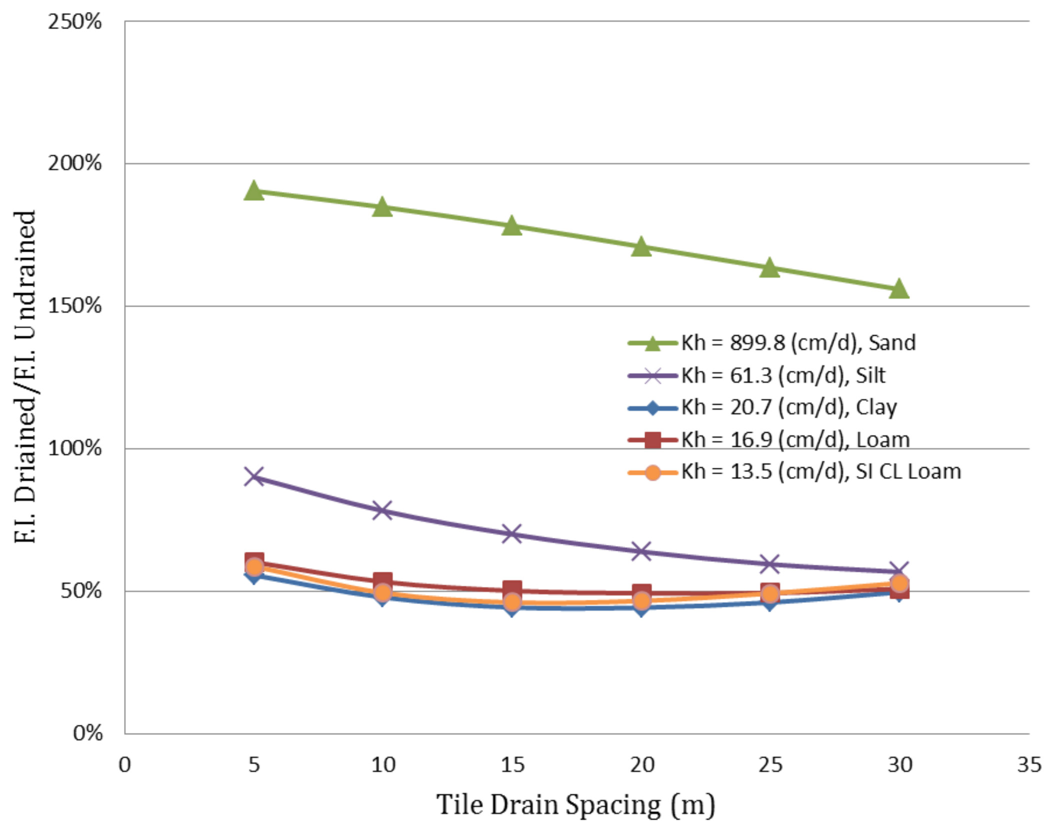


Figure 4-20 Effect of drain spacing on the change in flashiness, arranged by horizontal hydraulic conductivity for five soil textures.

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

This investigation was conducted to determine the change in hydrologic responses due to subsurface tile drainage at a hypothetical site in Ames, Iowa using 26 years of weather data. The results depict the hydrologic response of this hypothetical plot at the field scale where homogenous soil profiles are assumed. From the simulated results presented in Chapter 4, the effect of anthropogenic modifications to a landscape is determined to be strongly influenced by soil structural properties and hydraulic properties, along with rainfall regimes.

Artificial drainage systems provide water in the hydrologic system with a rapid subsurface outlet. Independent of rainfall regimes and cropping season, subsurface flows of drained landscapes always exceed that of undrained landscapes. It is inconclusive whether or not distance between adjacent parallel tile drains is indirectly proportional to peak baseflows.

Peak discharge during a storm event is heavily influenced by the soil hydraulic properties. Adding subsurface drains to soils with lower hydraulic conductivities (such as clay) tends to reduce peak flows during precipitation events by routing more of the rainfall through the soil matrix and increasing lag time. On the contrary, drains increase the peak flow in clays specifically during small precipitation events or during intense rainfalls with multiple peaks. As such, rainfall regimes do influence the hydrologic response though soil properties remain the dominant factor.

Conversely, adding subsurface drains to soils with higher hydraulic conductivities, such as sand, tends to increase peak flows during precipitation events. Soils with high hydraulic conductivities naturally have a high infiltration rate. Therefore, during an average precipitation event a large portion of the water is infiltrated and stored until it is eventually released through lateral seepage. By adding tile drains, this stored water is allowed a much quicker means of escape and is added to the streamflow, creating much flashier responses to precipitation events. On the contrary, drains decrease the peak flow in sand during intense storm events.

When the shrinking and cracking of clay soils is considered, tile drains minimally affect the flashiness of the flow regime. Macropores dominate water flow pathways into the soil matrix. The volume of macropores at the surface of the soil profile is indirectly proportional to flashiness index. Therefore, considering the geometry of macropores in the soil profile is particularly significant for future simulation of the physical processes in the soil water regime. Clay soils with low hydraulic conductivities behave similarly to sand soils with high hydraulic conductivities as the impact of macropores is considered.

Though soil properties and rainfall regimes remain indicative of the expected hydrologic response of tiled landscapes, it is important to point out that severe events of precipitation do not respond any differently to drained or undrained landscapes. Horton overland flow describes this phenomenon that occurs when the precipitation rate has exceeded the infiltration capacity. Even if the infiltration rate is not exceeded at the surface, large rainfall events tend to exhaust the soil storage capacity very quickly thus routing excess water out of the system via surface runoff. The tiles have a maximum carrying capacity and their contribution to the streamflow is negligible compared to the rapid surface runoff during large storm events. Therefore, maximum annual peak flows are not significantly impacted by additional subsurface drainage.

Hydrologic effects due to tile drains vary from soil to soil. The flashiness index is an ideal metric to characterize the hydrologic response of each scenario in order to normalize and compare the results. During years with heavy precipitation, soils with lower hydraulic conductivities show a 'saddle shape' relationship between the flashiness index and the distance between tile drains produces. The lowest point of the 'saddle' determines the ideal drain spacing for mitigating flashiness. For clay and loam soils, the ideal spacing for tile drains is approximately 15 m. Clay and loam have similar hydraulic conductivities and therefore respond to drainage in similar ways. By adding drains to these, flashiness can be reduced by up to 40%. Draining soils with higher hydraulic conductivities (sand and silt) only reduces the flashiness by up to 34%. Also, drained soils with higher hydraulic conductivities (sand and silt) show more sensitivity to the distance between tiles.

Future studies should investigate these conclusions in attempt to validate the findings. Complex interactions of natural physical processes between soils, water, and vegetation are difficult to simulate due to an enormous number of natural conditions which cannot be realistically simulated even by sophisticated models. Precise field measurements of soil hydraulic parameters are difficult, time-consuming, expensive, and/or have limitations to represent their spatial heterogeneity at the field scale. Crop growth errors may result due to nutrient shortage, weed competition, and pest or disease infestation which SWAP and WOFOST are not capable of predicting.

In the future, all soil water regime investigations should include accurate simulations of macropores. This study could be applied to many other soil types with various profiles. The results of this study depict the hydrologic response of a one-dimensional vertical soil column thereby limiting its practical application. By correctly scaling these physical processes, the flow regime changes due to artificial drainage systems could be examined at the subcatchment and catchment scales. Once the flow regime due to subsurface drainage developments are available, investigations of channelization improvement should follow since it is important to determine the hydrologic effect of agricultural drainage systems relative to the other anthropogenic modifications in watersheds. Continuance of comprehensive studies of artificial subsurface drainage can produce positive impacts on engineering, economic, and ecological environments.

APPENDIX

SWAP MODEL INPUT FILES FOR ONE SCENARIO

```
**********************************************************************************
* Filename: clay.swp
* Contents: Main input data
**********************************************************************************
* Comment area:
*
* Case: Water transport through a tiled field in Iowa.
*
*       This case is described as example in the SWAP user guide
**********************************************************************************

*   The main input file .swp contains the following sections:
*           - General section
*           - Meteorology section
*           - Crop section
*           - Soil water section
*           - Lateral drainage section
*           - Bottom boundary section
*           - Heat flow section
*           - Solute transport section


*** GENERAL SECTION ***

**********************************************************************************
* Part 1: Environment

  PROJECT   = 'clay'        ! Project description, [A80]
  PATHWORK  = '.\'                ! Path to work folder, [A80]
  PATHATM   = '.\data\weather\'   ! Path to folder with weather files, [A80]
  PATHCROP  = '.\data\crops\'     ! Path to folder with crop files, [A80]
  PATHDRAIN = '.\data\drainage\'  ! Path to folder with drainage files, [A80]
  SWSCRE    = 1                   ! Switch, display progression of simulation run:
                                 !   SWSCRE = 0:  no display to screen
                                 !   SWSCRE = 1:  display water balance to screen
                                 !   SWSCRE = 2:  display daynumber to screen
  SWERROR   = 1              ! Switch for printing errors to screen [Y=1, N=0]
**********************************************************************************


**********************************************************************************
* Part 2: Simulation period
*
  TSTART  = 01-jan-1987 ! Start date of simulation run, give day-month-year, [dd-mmm-yyyy]
  TEND    = 31-dec-2012 ! End   date of simulation run, give day-month-year, [dd-mmm-yyyy]
**********************************************************************************


**********************************************************************************
* Part 3: Output dates

* Number of output times during a day
  NPRINTDAY = 1       ! Number of output times during a day, [1..1000, I]

* If NPRINTDAY = 1, specify dates for output of state variables and fluxes
  SWMONTH = 0         ! Switch, output each month, [Y=1, N=0]

* If SWMONTH = 0, choose output interval and/or specific dates
  PERIOD = 1          ! Fixed output interval, ignore = 0, [0..366, I]
  SWRES  = 0          ! Switch, reset output interval counter each year, [Y=1, N=0]
  SWODAT = 0          ! Switch, extra output dates are given in table, [Y=1, N=0]
```

```
* If SWODAT = 1, list specific dates [dd-mmm-yyyy], maximum MAOUT dates:
  OUTDATINT =
  01-mar-1992
  31-jul-1992
* End of table

* Output times for overall water and solute balances in *.BAL and *.BLC file
* Output can be provided at a fixed date in a year or at different dates:
  SWYRVAR = 0          ! SWYRVAR = 0: each year output of balances at the same date
                       ! SWYRVAR = 1: output of balances at different dates

* If SWYRVAR = 0 specify fixed date:
  DATEFIX = 31 12      ! Specify day and month for output of yearly balances, [dd mm]

* If SWYRVAR = 1 specify all output dates [dd-mmm-yyyy], maximum MAOUT dates:
  OUTDAT =
  31-may-1992
  31-jul-1992
* End of table
**********************************************************************************


**********************************************************************************
* Part 4: Output files

* General information
  OUTFIL   = 'Result' ! Generic file name of output files, [A16]
  SWHEADER = 0         ! Print header at the start of each balance period, [Y=1, N=0]

* Optional files
  SWVAP  = 1         ! Switch, output profiles of moisture, solute and temperature, [Y=1, N=0]
  SWBLC  = 1         ! Switch, output file with detailed yearly water balance, [Y=1, N=0]
  SWATE  = 1         ! Switch, output file with soil temperature profiles, [Y=1, N=0]
  SWBMA  = 1         ! Switch, output file with water fluxes, only for macropore flow, [Y=1, N=0]
  SWDRF  = 1         ! Switch, output of drainage fluxes, only for extended drainage, [Y=1, N=0]
  SWSWB  = 1         ! Switch, output surface water reservoir, only for extended drainage, [Y=1, N=0]

* Output for water quality models (PEARL, ANIMO) or other specific use (SWAFO to DZNEW)

* Optional output files
  SWAFO  = 0         ! Switch, output file with formatted hydrological data
                     ! SWAFO = 0: no output
                     ! SWAFO = 1: output to a file named *.AFO
                     ! SWAFO = 2: output to a file named *.BFO

  SWAUN  = 0         ! Switch, output file with unformatted hydrological data
                     ! SWAUN = 0: no output
                     ! SWAUN = 1: output to a file named *.AUN
                     ! SWAUN = 2: output to a file named *.BUN

* Critical deviation of water balance; in case of larger deviation, an error file is created
(*.DWB.CSV)
  CRITDEVMASBAL = 0.00001  ! Critical Deviation in water balance during PERIOD [0.0..1.0 cm, R]

* If SWAFO = 1 or 2, or SWAUN = 1 or 2: fine vertical discretization can be lumped
  SWDISCRVERT = 0    ! SWDISCRVERT = 0: no conversion
                     ! SWDISCRVERT = 1: convert vertical discretization,

* If SWDISCRVERT = 1 then specify:
  NUMNODNEW = 6    ! New number of nodes [1..macp, I, -]
* List thickness of each compartment, total thickness should correspond to Soil Water Section, part 4
  DZNEW     = 10.0 10.0 10.0 20.0 30.0 50.0 ! thickness of compartments [1.0d-6...5.0d2, cm, R]
**********************************************************************************


*** METEOROLOGY SECTION ***

**********************************************************************************
* General data
```

```
* File name
  METFIL = 'amesdetail' ! File name of meteorological data without extension .YYY, [A200]
                           ! Extension is equal to last 3 digits of year, e.g. 003 denotes year 2003

* Use of reference evapotranspiration data from meteorological file instead of basic data
  SWETR  =  0           ! Switch, use reference ET values of meteo file [Y=1, N=0]

* If SWETR = 0, specify:
  LAT    =   41.9       ! Latitude of meteo station, [-60..60 degrees, R, North = +]
  ALT    =   240.0      ! Altitude of meteo station, [-400..3000 m, R]
  ALTW   =   10.0       ! Altitude of wind speed measurement (10 m is default) [0..99 m, R]

* Use of detailed meteorological records for both ET and rainfall (< 1 day) instead of daily values
  SWMETDETAIL = 1       ! Switch, use detailed meteorological records of both ET and rainfall [Y=1,
N=0]

* In case of detailed meteorological weather records (SWMETDETAIL = 1), specify:
  NMETDETAIL = 24       ! Number of weather data records per day, [1..96 -, I]

* In case of daily meteorological weather records (SWMETDETAIL = 0):
  SWETSINE = 1          ! Switch, distribute daily Tp and Ep according to sinus wave [Y=1, N=0]

  SWRAIN =  3           ! Switch for use of actual rainfall intensity (only if SWMETDETAIL = 0):
                        ! SWRAIN = 0: Use daily rainfall amounts
                        ! SWRAIN = 1: Use daily rainfall amounts + mean intensity
                        ! SWRAIN = 2: Use daily rainfall amounts + duration
                        ! SWRAIN = 3: Use short time rainfall intensities, as supplied in separate
file

* If SWRAIN = 1, then specify mean rainfall intensity RAINFLUX [0.d0..1000.d0 mm/d, R]
* as function of time TIME [0..366 d, R], maximum 30 records
   TIME    RAINFLUX
    1.0        20.0
  360.0        20.0
* End of table

* If SWRAIN = 3, then specify file name of file with detailed rainfall data
  RAINFIL = 'amesdetail'   ! File name of detailed rainfall data without extension .YYY, [A200]
                              ! Extension is equal to last 3 digits of year, e.g. 003 denotes year
2003
**********************************************************************************


*** CROP SECTION ***

**********************************************************************************
* Part 1: Crop rotation scheme during simulation period

* Specify information for each crop (maximum MACROP):
* CROPSTART  = date of crop emergence, [dd-mmm-yyyy]
* CROPEND    = date of crop harvest, [dd-mmm-yyyy]
* CROPNAME   = crop name, [A40]
* CROPFIL    = name of file with crop input parameters without extension .CRP, [A40]
* CROPTYPE   = type of crop model: simple = 1, detailed general = 2, detailed grass = 3

  CROPSTART      CROPEND       CROPNAME   CROPFIL     CROPTYPE
  10-may-1987    17-oct-1987   'Corn'     'GmaizeD'     2
  10-may-1988    17-oct-1988   'Corn'     'GmaizeD'     2
  10-may-1989    17-oct-1989   'Corn'     'GmaizeD'     2
  10-may-1990    17-oct-1990   'Corn'     'GmaizeD'     2
  10-may-1991    17-oct-1991   'Corn'     'GmaizeD'     2
  10-may-1992    17-oct-1992   'Corn'     'GmaizeD'     2
  10-may-1993    17-oct-1993   'Corn'     'GmaizeD'     2
  10-may-1994    17-oct-1994   'Corn'     'GmaizeD'     2
  10-may-1995    17-oct-1995   'Corn'     'GmaizeD'     2
  10-may-1996    17-oct-1996   'Corn'     'GmaizeD'     2
  10-may-1997    17-oct-1997   'Corn'     'GmaizeD'     2
  10-may-1998    17-oct-1998   'Corn'     'GmaizeD'     2
  10-may-1999    17-oct-1999   'Corn'     'GmaizeD'     2
  10-may-2000    17-oct-2000   'Corn'     'GmaizeD'     2
```

```
  10-may-2001    17-oct-2001   'Corn'     'GmaizeD'     2
  10-may-2002    17-oct-2002   'Corn'     'GmaizeD'     2
  10-may-2003    17-oct-2003   'Corn'     'GmaizeD'     2
  10-may-2004    17-oct-2004   'Corn'     'GmaizeD'     2
  10-may-2005    17-oct-2005   'Corn'     'GmaizeD'     2
  10-may-2006    17-oct-2006   'Corn'     'GmaizeD'     2
  10-may-2007    17-oct-2007   'Corn'     'GmaizeD'     2
  10-may-2008    17-oct-2008   'Corn'     'GmaizeD'     2
  10-may-2009    17-oct-2009   'Corn'     'GmaizeD'     2
  10-may-2010    17-oct-2010   'Corn'     'GmaizeD'     2
  10-may-2011    17-oct-2011   'Corn'     'GmaizeD'     2
  10-may-2012    17-oct-2012   'Corn'     'GmaizeD'     2
* End of table
**********************************************************************************


**********************************************************************************
* Part 2: Fixed irrigation applications

* Switch for fixed irrigation applications
  SWIRFIX = 0    ! SWIRFIX = 0: no irrigation applications are prescribed
                 ! SWIRFIX = 1: irrigation applications are prescribed

* If SWIRFIX = 1, specify:

* Switch for separate file with fixed irrigation applications
  SWIRGFIL  = 0  ! SWIRGFIL = 0: data are specified in the .swp file
                 ! SWIRGFIL = 1: data are specified in a separate file

* If SWIRGFIL  = 0 specify information for each fixed irrigation event (max. MAIRG):
* IRDATE   = date of irrigation, [dd-mmm-yyyy]
* IRDEPTH  = amount of water, [0.0..100.0 cm, R]
* IRCONC   = concentration of irrigation water, [0.0..1000.0 mg/cm3, R]
* IRTYPE   = type of irrigation: sprinkling = 0, surface = 1

       IRDATE   IRDEPTH     IRCONC   IRTYPE
  05-apr-1992       0.5     1000.0        1
* end of table

* If SWIRGFIL  = 1, specify name of file with data of fixed irrigation applications:
  IRGFIL = 'testirri'      ! File name without extension .IRG [A16]
**********************************************************************************


*** SOIL WATER SECTION ***

**********************************************************************************
* Part 1: Initial soil moisture condition

 SWINCO = 2 ! Switch, type of initial soil moisture condition:
            ! 1 = pressure head as function of depth is input
            ! 2 = pressure head of each compartment is in hydrostatic equilibrium
            !     with initial groundwater level
            ! 3 = read final pressure heads from output of previous Swap simulation

* If SWINCO = 1, specify (maximum MACP):
* ZI = soil depth, [-10000..0 cm, R]
* H  = initial soil water pressure head, [-1.d10..1.d4 cm, R]

      ZI         H
    -0.5     -93.0
  -195.0     120.0
* End of table

* If SWINCO = 2, specify:
  GWLI   = -110.0          ! Initial groundwater level, [-10000..100 cm, R]

* If SWINCO = 3, specify:
  INIFIL = 'result.end'    ! name of final with extension .END [a200]
**********************************************************************************
```

```
**********************************************************************************
* Part 2: Ponding, runoff and runon

* Ponding
  PONDMX  = 1.25  ! In case of ponding, minimum thickness for runoff, [0..1000 cm, R]

* Runoff
  RSRO    =  1.0 ! Drainage resistance for surface runoff [0.001..1.0 d, R]
  RSROEXP =  1.0 ! Exponent in drainage equation of surface runoff [0.1..10.0 -, R]

* Runon
* Specify whether runon data are provided in extra input file
  SWRUNON = 0   ! 0 = No input of runon data
                ! 1 = Runon data are provided in extra input file

* If SWRUNON = 1, specify name of file with runon input data
* This file may be an output *.inc file (with only 1 header) of a previous Swap-simulation
  RUFIL = 'runon.inc' ! File name with extension [A80]
**********************************************************************************


**********************************************************************************
* Part 3: Soil evaporation
*
  SWCFBS = 0    ! Switch for use of soil factor CFBS to calculate Epot from ETref
                ! 0 = CFBS is not used
                ! 1 = CFBS is used

* If SWCFBS = 1, specify soil factor CFBS:
  CFBS   = 1.0 ! Coefficient to derive Epot from ETref [0.1..1.5 -, R]
*
*
  SWREDU = 1    ! Switch, method for reduction of potential soil evaporation:
                ! 0 = reduction to maximum Darcy flux
                ! 1 = reduction to maximum Darcy flux and to maximum Black (1969)
                ! 2 = reduction to maximum Darcy flux and to maximum Bo/Str. (1986)

 COFRED = 0.40 ! Soil evaporation coefficient of Black, [0..1 cm/d1/2, R],
                ! or Boesten/Stroosnijder, [0..1 cm1/2, R]

 RSIGNI =  0.5 ! Minimum rainfall to reset method of Black [0..1 cm/d, R]
**********************************************************************************


**********************************************************************************
* Part 4: Vertical discretization of soil profile

* Specify the following data (maximum MACP lines):
* ISOILLAY = number of soil layer, start with 1 at soil surface, [1..MAHO, I]
* ISUBLAY  = number of sub layer, start with 1 at soil surface, [1..MACP, I]
* HSUBLAY  = height of sub layer, [0.0..1000.0 cm, R]
* HCOMP    = height of compartments in this layer, [0.0..1000.0 cm, R]
* NCOMP    = number of compartments in this layer (= HSUBLAY/HCOMP), [1..MACP, I]

 ISOILLAY ISUBLAY  HSUBLAY    HCOMP    NCOMP
     1       1       10.0      1.0       10
     1       2       20.0      1.0       20
     2       3       30.0      2.5       12
     2       4      330.0      5.0       66
* end of table
**********************************************************************************


**********************************************************************************
* Part 5: Soil hydraulic functions

* Switch for Mualem - van Genuchten parameters or detailed tabels:
  SWSOPHY = 0    ! 0 = Mualem - van Genuchten parameters
```

```
                ! 1 = Detailed tables

* If SWSOPHY = 0, specify for each soil layer (maximum MAHO):
* ISOILLAY1 = number of soil layer, as defined in part 4 [1..MAHO, I]
* ORES    = Residual water content, [0..0.4 cm3/cm3, R]
* OSAT    = Saturated water content, [0..0.95 cm3/cm3, R]
* ALFA    = Shape parameter alfa of main drying curve, [0.0001..1 /cm, R]
* NPAR    = Shape parameter n, [1..4 -, R]
* KSAT    = Saturated vertical hydraulic conductivity, [1.d-5..1000 cm/d, R]
* LEXP    = Exponent in hydraulic conductivity function, [-25..25 -, R]
* ALFAW   = Alfa parameter of main wetting curve in case of hysteresis, [0.0001..1 /cm, R]
* H_ENPR = Air entry pressure head [-40.0..0.0 cm, R]

  ISOILLAY1  ORES     OSAT      ALFA    NPAR     KSAT      LEXP    ALFAW   H_ENPR
       1     0.098   0.459    0.0150   1.253    14.76    -1.561   0.0454   0.0
       2     0.098   0.459    0.0150   1.253    14.76    -1.561   0.0454   0.0
* --- end of table

* If SWSOPHY = 1, specify names of input files [A80] with soil hydraulic tables for each soil layer:
  FILENAMESOPHY = 'topsoil_sand_B2.csv', 'subsoil_sand_O2.csv'
**********************************************************************************


**********************************************************************************
* Part 6: Hysteresis of soil water retention function

* Switch for hysteresis:
  SWHYST = 0    ! 0 = no hysteresis
               ! 1 = hysteresis, initial condition wetting
               ! 2 = hysteresis, initial condition drying

* If SWHYST = 1 or 2, specify:
  TAU = 0.2     ! Minimum pressure head difference to change wetting-drying, [0..1 cm, R]
**********************************************************************************


**********************************************************************************
* Part 7: Maximum rooting depth

  RDS   = 200.0   ! Maximum rooting depth allowed by the soil profile, [1..5000 cm, R]
**********************************************************************************


**********************************************************************************
* Part 8: Similar media scaling of soil hydraulic functions

  SWSCAL = 0 ! Switch for similar media scaling [Y=1, N=0]; no hysteresis is allowed
             ! in case of similar media scaling (SWHYST = 0)

* If SWSCAL = 1, specify:
  NSCALE = 3 ! Number of simulation runs, [1..MASCALE, I]

* Supply the scaling factors for each simulation run and each soil layer:

  RUN     SOIL1
   1       0.5
   2       1.0
   3       2.0
   4       1.0
   5       3.0
* End of table
**********************************************************************************


**********************************************************************************
* Part 9: Preferential flow due to macropores
  SwMacro = 0     ! Switch for macro pores, [0..1, I]
                  ! 0 = no macropore flow
                  ! 1 = macropore flow
```

```
* If SwMacro = 1, specify parameters for macropore flow:
  Z_AH = -26.0    ! Depth bottom A-horizon [-1000..0 cm, R]
  Z_IC = -90.0    ! Depth bottom Internal Catchment (IC) domain [-1000..0 cm, R]
  Z_ST = -180.0   ! Depth bottom Static macropores [-1000..0 cm, R]
  VlMpStSs = 0.02 ! Volume fraction of Static Macropores at Soil Surface [0..0.5 cm3/cm3, R]
  PpIcSs = 0.6    ! Proportion of IC domain at Soil Surface [0..0.99 -, R]
  NumSbDm = 4     ! Number of Sub-domains in IC domain [0..MaDm-2 -, I]
  PowM = 0.8      ! Power M for frequency distrib. curve IC domain (OPTIONAL, default 1.0) [0..100 -,
R]
  RZah = 0.0      ! Fraction macropores ended at bottom A-horizon [OPTIONAL, default 0.0] [0..1 -, R]
  SPoint = 1.0    ! Symmetry Point for freq. distr. curve [OPTIONAL, default 1.0] [0..1 -, R]
  SwPowM = 0      ! Switch for double convex/concave freq. distr. curve (OPTIONAL, Y=1, N=0; default:
0) [0..1 -, I]
  DiPoMi = 10.0   ! Minimal diameter soil polygons (shallow) [0.1..1000 cm, R]
  DiPoMa = 50.0   ! Maximal diameter soil polygons (deep) [0.1..1000 cm, R]
  ZDiPoMa = -180.0! Depth below which diameter polygons is max. (OPTIONAL, default 0.) [-1000..0 cm,
R]

* Start of Table with shrinkage characteristics
* ISOILLAY3 = indicator (number) of soil layer, as defined in part 4 [1..MAHO, I]
* SWSoilShr = Switch for kind of soil for shrinkage curve: 0 = rigid, 1 = clay, 2 = peat [0..2 -, I]
* SWShrInp  = Switch for determining shrinkage curve [1..2 -, I]:  1 = parameters of curve are given;
*                                                                  2 = typical points of curve given;
*                                                                  3 = (only peat) intersection
points
*                                                                      of 3-straight-line-model
given
* ThetCrMP  = Threshold moisture content below which horizontal shrinkage [0..1 cm3/cm3, R]
* GeomFac   = Geometry factor (3.0 = isotropic shrinkage), [0..100, R]
*
* ShrParA to ShrParE = parameters for describing shrinkage curves,
*                      depending on combination of SWSoilShr and SwShrInp [-1000..1000, R]:
*          SWSoilShr = 0               : 0 variables required (all dummies)
*          SWSoilShr = 1, SwShrInp 1 = : 3 variables required (ShrParA to ShrParC) (rest dummies)
*          SWSoilShr = 1, SwShrInp 2 = : 2 variables required (ShrParA to ShrParB) (rest dummies)
*          SWSoilShr = 2, SwShrInp 1 = : 5 variables required (ShrParA to ShrParE)
*          SWSoilShr = 2, SwShrInp 2 = : 5 variables required (ShrParA to ShrParE)
*          SWSoilShr = 2, SwShrInp 3 = : 4 variables required (ShrParA to ShrParD) (rest dummy)

  ISOILLAY3  SWSoilShr  SwShrInp  ThetCrMP  GeomFac  ShrParA  ShrParB  ShrParC  ShrParD  ShrParE
      1          1          2       0.3990      3.0    0.344   0.6879      0.0      0.0      0.0
      2          1          2       0.3864      3.0    0.344   0.6879      0.0      0.0      0.0
* End of Tabel with shrinkage characteristics

ZnCrAr = -5.0    ! Depth at which crack area of soil surface is calculated [-100..0 cm, R]

**********************************************************************************
* Start of Tabel with sorptivity characteristics

* ISOILLAY4   = Indicator (number) of soil layer, as defined in part 4 [1..MAHO, I]
* SWSorp      = Switch for kind of sorptivity function [1..2 -, I]:
*               1 = calculated from hydraulic functions according to Parlange
*               2 = empirical function from measurements
* SorpFacParl = Factor for modifying Parlange function (OPTIONAL, default 1.0) [0..100 -, R]
* SorpMax     = Maximal sorptivity at theta residual [0..100 cm/d**0.5, R]
* SorpAlfa    = Fitting parameter for empirical sorptivity curve [-10..10 -, R]

  ISOILLAY4   SwSorp   SorpFacParl   SorpMax   SorpAlfa
      1          1         0.33         0.0        0.0
      2          1         0.33         0.0        0.0
* End of Tabel with sorptivity characteristics
*
  ShapeFacMp = 1.0 ! Shape factor for lateral Darcy flow (theoret. 1-2) [0..100 -, R]
  CritUndSatVol = 0.1 ! Critical value for under-saturation volume [0..10 -, R]
*
  SwDrRap = 1 ! Switch for simulating rapid drainage,[Y=1, N=0]
  RapDraResRef = 15. ! Reference rapid drainage resistance [0..1.E+10 /d, R]
  RapDraReaExp = 1.0 ! Exponent for reaction rapid drainage to dynamic crack width [0..100 -, R]
  NumLevRapDra = 1 ! Number of drainage system connected to rapid drainage [1..NRLEVS, -, I]
```

```
* Threshold value for ponding (cm) on soil surface before overland flow into macropores starts
  PNDMXMP = 0.0 ! [0.0 .. 10.0, cm, R]

  SWDARCY = 0

**********************************************************************************


**********************************************************************************
* Part 10: Snow and frost

* Snow
  SWSNOW = 0   ! Switch, calculate snow accumulation and melt, [Y=1, N=0]

* If SWSNOW = 1, specify:
  SNOWINCO = 0.0       ! Initial snow water equivalent, [0.0...1000.0 cm, R]
  TEPRRAIN = 0.0       ! Temperature above which all precipitation is rain,[ 0.0...5.0 °C, R]
  TEPRSNOW = -2.0      ! Temperature below which all precipitation is snow,[-5.0...0.0 °C, R]
  SNOWCOEF = 0.3       ! Snowmelt calibration factor, [0.0...10.0 -, R]

* Frost
  SWFROST = 0  ! Switch, in case of frost: reduce soil water flow, [Y=1, N=0]

* If SWFROST = 1, then specify soil temperature to start end end flux-reduction
  tfroststa = 0.0      ! Soil temperature (°C) where reduction of water fluxes starts [-10.0,5.0, oC,
R]
  tfrostend = -1.0     ! Soil temperature (°C) where reduction of water fluxes ends [-10.0,5.0, oC,
R]
**********************************************************************************


**********************************************************************************
* Part 11 Numerical solution of Richards' equation

  DTMIN         = 1.0d-6     ! Minimum timestep, [1.d-7..0.01 d, R]
  DTMAX         = 0.2        ! Maximum timestep, [ 0.01..0.5 d, R]
  GWLCONV       = 100.0      ! Maximum dif. groundwater level between iterations, [1.d-5..1000 cm, R]
  CritDevh1Cp   = 1.0d-2     ! Maximum relative difference in pressure heads per compartment, [1.0d-
10..0.1 -, R]
  CritDevh2Cp   = 1.0d-1     ! Maximum difference in pressure heads per compartment, [1.0d-10..1.0
cm, R]
  CritDevPondDt = 1.0d-4     ! Maximum water balance error of ponding layer, [1.0d-6..0.1 cm, R]
  MaxIt         = 30         ! Maximum number of iteration cycles, [5..100 -, I]
  MaxBackTr     = 3          ! Maximum number of back track cycles within an iteration cycle, [1..10
-,I]

* Switch for mean of hydraulic conductivity, [1..4 -, I]:
* 1 = unweighted  arithmic mean; 2 = weighted  arithmic mean
* 3 = unweighted geometric mean; 4 = weighted geometric mean
  SWkmean = 1

* Switch for explicit/implicit solution Richards equation with hydraulic conductivity, [1..2 -, I]:
  SWkImpl = 0    ! 0 = explicit solution
                 ! 1 = implicit solution
**********************************************************************************


*** LATERAL DRAINAGE SECTION ***

**********************************************************************************
* Specify whether lateral drainage to surface water should be included

  SWDRA = 1  ! Switch, simulation of lateral drainage:
             ! 0 = No simulation of drainage
             ! 1 = Simulation with basic drainage routine
             ! 2 = Simulation of drainage with surface water management

* If SWDRA = 1 or SWDRA = 2 specify name of file with drainage input data:
  DRFIL = '25m.tiles' ! File name with drainage input data without extension .DRA, [A16]
**********************************************************************************
```

```
*** BOTTOM BOUNDARY SECTION ***

**********************************************************************************
* Bottom boundary condition

  SWBBCFILE  = 0    ! Switch for file with bottom boundary conditions:
                    ! SWBBCFILE = 0: data are specified in the .swp file
                    ! SWBBCFILE = 1: data are specified in a separate file

* If SWBBCFILE = 1 specify name of file with bottom boundary conditions:
  BBCFIL = ' '      ! File name without extension .BBC [A16]

* If SWBBCFILE = 0, select one of the following options:
             ! 1  Prescribe groundwater level
             ! 2  Prescribe bottom flux
             ! 3  Calculate bottom flux from hydraulic head of deep aquifer
             ! 4  Calculate bottom flux as function of groundwater level
             ! 5  Prescribe soil water pressure head of bottom compartment
             ! 6  Bottom flux equals zero
             ! 7  Free drainage of soil profile
             ! 8  Free outflow at soil-air interface

 SWBOTB = 6  ! Switch for bottom boundary [1..8,-,I]

* Options 6,7 and 8 require no additional bottom input data
**********************************************************************************


**********************************************************************************
* SWBOTB = 1  Prescribe groundwater level

* specify DATE [dd-mmm-yyyy] and groundwater level [cm, -10000..1000, R]

        DATE1    GWLEVEL         ! (max. MABBC records)
  01-mar-1992     -95.0
  31-dec-1992     -95.0
* End of table
**********************************************************************************


**********************************************************************************
* SWBOTB = 2   Prescribe bottom flux

* Specify whether a sine or a table are used to prescribe the bottom flux:
  SW2    = 2      ! 1 = sine function; 2 = table

* In case of sine function (SW2 = 1), specify:
  SINAVE =  0.1   ! Average value of bottom flux, [-10..10 cm/d, R, + = upwards]
  SINAMP =  0.05  ! Amplitude of bottom flux sine function, [-10..10 cm/d, R]
  SINMAX =  91.0  ! Time of the year with maximum bottom flux, [1..366 d, R]

* In case of table (SW2 = 2), specify date [dd-mmm-yyyy] and bottom flux QBOT2
* [-100..100 cm/d, R, positive = upwards]:

        DATE2     QBOT2           ! (maximum MABBC records)
  01-mar-1992       0.1
  30-jun-1992       0.2
  23-jul-1992      0.15
* End of table
**********************************************************************************


**********************************************************************************
* SWBOTB = 3    Calculate bottom flux from hydraulic head in deep aquifer

* Switch to suppress vertical hydraulic resistance between model bottom and groundwater level
  SWBOTB3RESVERT = 0 ! 0 = Include vertical hydraulic resistance
                     ! 1 = Suppress vertical hydraulic resistance
```

```
* Switch for numerical solution of bottom flux: 0 = explicit, 1 = implicit
  SWBOTB3IMPL = 0    ! 0 = explicit solution (choose always when SHAPE < 1.0)
                     ! 1 = implicit solution

* Specify:
  SHAPE  =   0.79  ! Shape factor to derive average groundwater level, [0.0..1.0 -, R]
  HDRAIN =  -110.0 ! Mean drain base to correct for average groundwater level, [-10000..0 cm, R]
  RIMLAY =   500.0 ! Vertical resistance of aquitard, [0..10000 d, R]

* Specify whether a sine function or a table are used to prescribe hydraulic head of deep aquifer:
  SW3    = 1       ! 1 = sine function;  2 = table

* In case of sine function (SW3  = 1), specify:
  AQAVE  =  -140.0 ! Average hydraulic head in underlaying aquifer, [-10000..1000 cm, R]
  AQAMP  =    20.0 ! Amplitude hydraulic head sinus wave, [0..1000 cm, R]
  AQTMAX =  120.0  ! First time of the year with maximum hydraulic head, [1..366 d, R]
  AQPER  =  365.0  ! Period hydraulic head sinus wave, [1..366 d, I]

* In case of table (SW3  = 2), specify date [dd-mmm-yyyy] and average hydraulic head
* HAQUIF in underlaying aquifer [-10000..1000 cm, R]:

        DATE3    HAQUIF           ! (maximum MABBC records)
  01-mar-1992     -95.0
  15-mar-1992    -110.0
  30-mar-1992     -70.0
* End of table

* An extra groundwater flux can be specified which is added to above specified flux
  SW4    = 1       ! 0 = no extra flux; 1 = include extra flux

* If SW4 = 1, specify date [dd-mmm-yyyy] and bottom flux QBOT4 [-100..100 cm/d, R,
* positive = upwards]:

        DATE4     QBOT4           ! (maximum MABBC records)
  01-mar-1992       1.0
  15-mar-1992     -0.15
  30-mar-1992       1.2
* End of table
**********************************************************************************


**********************************************************************************
* SWBOTB = 4     Calculate bottom flux as function of groundwater level

* Specify whether an exponential relation or a table is used to calculate the bottom flux
* from the groundwater level:
  SWQHBOT = 2       ! 1 = exponential relation;  2 = table

* In case of an exponential relation (SWQHBOT  = 1),
* specify coefficients of relation qbot = A exp (B*abs(groundwater level))
  COFQHA =  0.1  ! Coefficient A, [-100..100 cm/d, R]
  COFQHB =  0.5  ! Coefficient B  [-1..1 /cm, R]

* In case of a table (SWQHBOT  = 2),
* specify groundwaterlevel Htab [-10000..1000, cm, R]  and bottom flux QTAB [-100..100 cm/d, R]
* Htab is negative below the soil surface, Qtab is negative when flux is downward.
  HTAB   QTAB
  -0.1   -0.35
  -70.0  -0.05
 -125.0  -0.01
**********************************************************************************


**********************************************************************************
* SWBOTB = 5     Prescribe soil water pressure head of bottom compartment

* Specify DATE [dd-mmm-yyyy] and bottom compartment pressure head HBOT5 [-1.d10..1000 cm, R]:

        DATE5     HBOT5           ! (maximum MABBC records)
```

```
  01-mar-1992     -95.0
  15-mar-1992    -110.0
  30-mar-1992     -70.0
* End of table
**********************************************************************************


*** HEAT FLOW SECTION ***

**********************************************************************************
* Part 1: Specify whether simulation includes heat flow

  SWHEA  = 1 ! Switch for simulation of heat transport, [Y=1, N=0]
**********************************************************************************

**********************************************************************************
* Part 2: Heat flow calculation method

  SWCALT = 1     ! Switch for method: 1 = analytical method, 2 = numerical method
**********************************************************************************

**********************************************************************************
* Part 3: Analytical method

* If SWCALT = 1 specify the following heat parameters:
  TAMPLI = 10.0 ! Amplitude of annual temperature wave at soil surface, [0..50 C, R]
  TMEAN  = 15.0 ! Mean annual temperature at soil surface, [5..30 C, R]
  TIMREF = 90.0 ! Time in the year with top of sine temperature wave [1..366 d, R]
  DDAMP  = 50.0 ! Damping depth of temperature wave in soil, [0..500 cm, R]
**********************************************************************************

**********************************************************************************
* Part 4: Numerical method

* If SWCALT = 2 specify the following heat parameters:

* Specify for each soil type the soil texture (g/g mineral parts)
* and the organic matter content (g/g dry soil):

  ISOILLAY5  PSAND    PSILT    PCLAY    ORGMAT           ! (maximum MAHO records)
     1         0.80     0.15     0.05     0.100
     2         0.80     0.15     0.05     0.100
* End of table

* If SWINCO = 1 or 2, list initial temperature TSOIL [-20..40 C, R] as function of
* soil depth ZH [-1.0d5..0 cm, R]:

      ZH    TSOIL   ! (maximum MACP records)
   -10.0     15.0
   -40.0     12.0
   -70.0     10.0
   -95.0      9.0
* End of table

* Define top boundary condition:
  SwTopbHea = 1     ! 1 = use air temperature of meteo input file as top boundary
                    ! 2 = use measured top soil temperature as top boundary

* If SwTopbHea = 2, specify name of input file with soil surface temperatures
  TSOILFILE = 'Haarweg' ! File name without extension .TSS, [A16]

* Define bottom boundary condition:
  SwBotbHea = 1     ! 1 = no heat flux; 2 = prescribe bottom temperature

* If SwBotbHea = 2, specify a tabel with dates and temperatures at bottom boundary

  DATET           TBOT   ! (maximum MABBC records)
  01-mar-1982    -15.0
  15-mar-1982    -20.0
  30-mar-1982    -10.0
```

```
* End of table
**********************************************************************************


*** SOLUTE SECTION ***

**********************************************************************************
* Part 1: Specify whether simulation includes solute transport

  SWSOLU = 0 ! Switch for simulation of solute transport, [Y=1, N=0]
**********************************************************************************


**********************************************************************************
* Part 2: Top boundary and initial condition

  CPRE = 0.0    ! Solute concentration in precipitation, [1..100 mg/cm3, R]

* If SWINCO = 1 or 2, list initial solute concentration CML [1..1000 mg/cm3, R]
* as function of soil depth ZC [-10000..0 cm, R], max. MACP records:
      ZC        CML
   -10.0        0.0
   -95.0        0.0
* End of table
**********************************************************************************


**********************************************************************************
* Part 3: Miscellaneous parameters as function of soil depth

* Specify for each soil layer (maximum MAHO)
* ISOILLAY6 = number of soil layer, as defined in soil water section (part 4) [1..MAHO, I]
* LDIS      = dispersion length, [0..100 cm, R]
* KF        = Freundlich adsorption coefficient, [0..100 cm3/mg, R]
* BDENS     = dry soil bulk density, [500..3000 mg/cm3, R]
* DECPOT    = potential decomposition rate, [0..10 /d, R]

 ISOILLAY6     LDIS          KF     BDENS  DECPOT
     1         5.00   0.0001389   1315.00     0.0
* --- end of Table
**********************************************************************************


**********************************************************************************
* Part 4: Diffusion constant and solute uptake by roots

  DDIF = 0.0    ! Molecular diffusion coefficient, [0..10 cm2/day, R]
  TSCF = 0.0    ! Relative uptake of solutes by roots, [0..10 -, R]
**********************************************************************************


**********************************************************************************
* Part 5: Adsorption

  SWSP = 0      ! Switch, consider solute adsorption, [Y=1, N=0]

* In case of adsorption (SWSP = 1), specify:
  FREXP = 0.9   ! Freundlich exponent, [0..10 -, R]
  CREF  = 1.0   ! Reference solute concentration for adsorption, [0..1000 mg/cm3, R]
**********************************************************************************


**********************************************************************************
* Part 6: Decomposition

  SWDC = 0      ! Switch, consideration of solute decomposition, [Y=1, N=0]

* In case of solute decomposition (SWDC = 1), specify:
  GAMPAR = 0.0  ! Factor reduction decomposition due to temperature, [0..0.5 /°C, R]
  RTHETA = 0.3  ! Minimum water content for potential decomposition, [0..0.4 cm3/cm3, R]
```

```
  BEXP   = 0.7  ! Exponent in reduction decomposition due to dryness, [0..2 -, R]

* List the reduction of pot. decomposition for each soil type, [0..1 -, R]:

  ISOILLAY7  FDEPTH           ! (maximum MAHO records)
      1       1.00
      2       0.65
* End of table
**********************************************************************************


**********************************************************************************
* Part 7: Solute residence in the saturated zone

  SWBR = 0       ! Switch, consider mixed reservoir of saturated zone [Y=1, N=0]

* Without mixed reservoir (SWBR = 0), specify:
  CDRAIN = 0.1   ! solute concentration in groundwater, [0..100 mg/cm3, R]

* In case of mixed reservoir (SWBR = 1), specify:
  DAQUIF = 110.0 ! Thickness saturated part of aquifer, [0..10000 cm, R]
  POROS  = 0.4   ! Porosity of aquifer, [0..0.6 -, R]
  KFSAT  = 0.2   ! Linear adsorption coefficient in aquifer, [0..100 cm3/mg, R]
  DECSAT = 1.0   ! Decomposition rate in aquifer, [0..10 /d, R]
  CDRAINI = 0.2  ! Initial solute concentration in groundwater, [0..100 mg/cm3, R]
**********************************************************************************

* End of the main input file .SWP!
```

```
**********************************************************************************************
* Filename: GMaizeD.CRP
* Contents: SWAP 3.2 - Data for detailed crop model
**********************************************************************************************
*c Grain maize (Zea mays L.)
**********************************************************************************************

*** PLANT GROWTH SECTION ***

**********************************************************************************************
* Part 1: Crop factor or crop height

  SWCF = 1 ! choice between crop factor [=1] or crop height [=2]
* Choose crop factor if ETref is used, either from meteo input file (SWETR = 1) or with Penman-
Monteith
* Choose crop height if Penman-Monteith should be used with actual crop height, albedo and resistance

* If SWCF = 1, list crop factor CF [0.5..1.5, R],   as function of dev. stage DVS [0..2 -,R]:
* If SWCF = 2, list crop height CH [0..1000 cm, R], as function of dev. stage DVS [0..2 -,R]:
*  (maximum 36 records)

    DVS       CH     CF
    0.0      5.0    1.0
    1.0    199.0    1.2
    2.0    244.0    1.2

* End of Table

* If SWCF = 2, list crop specifi values for:
  ALBEDO =   0.23 ! crop reflection coefficient [0..1.0 -, R]
  RSC    =   70.0 ! Minimum canopy resistance [0..10^6 s/m, R]
  RSW    =    0.0 ! Canopy resistance of intercepted water [0..10^6 s/m, R]
**********************************************************************************************


**********************************************************************************************
* Part 2 : Crop development

  IDSL   =        0 ! Switch for crop development:
*                     0 = Crop development before anthesis depends on temperature only
*                     1 = Crop development before anthesis depends on daylenght e only
*                     2 = Crop development before anthesis depends on both

* If IDSL = 1 or 2, specify:
  DLO    = 1.0     ! Minimum day length for optimum crop development [0..24 h, R]
  DLC    = 0.0     ! Shortest day length for any development, [0..24 h, R]

* If IDSL = 0 or 2 specify:
  TSUMEA =   750.00 ! Temperature sum from emergence to anthesis, [0..10000 C, R]
  TSUMAM =   859.00 ! Temperature sum from anthesis to maturity  [0..10000 C, R]

* List increase in temperature sum [0..60 C, R] as function of daily average temp. [0..100 C, R]
*         TAV  DTSM    (maximum 15 records)
  DTSMTB =
            0.00   0.00
            8.00   0.00
           30.00  22.00
           35.00  22.00
* End of Table

  DVSEND =      2.00 ! development stage at harvest [-]
**********************************************************************************************


**********************************************************************************************
* Part 3: Initial values

  TDWI   = 20.00    ! Initial total crop dry weight [0..10000 kg/ha, R]
  LAIEM  =  0.02604 ! Leaf area index at emergence [0..10 m2/m2, R]
  RGRLAI =  0.0500  ! Maximum relative increase in LAI [0..1 m2/m2/d, R]
```

```
********************************************************************************************

********************************************************************************************
* Part 4: Green surface area

  SPA    =  0.000 ! Specific pod area  [0..1 ha/kg, R]
  SSA    =  0.000 ! Specific stem area [0..1 ha/kg, R]
  SPAN   = 40.0   ! Life span under leaves under optimum conditions, [0..366 d, R]
  TBASE  =  8.0   ! Lower threshold temperature for ageing of leaves ,[-10..30 C, R]

* List specific leaf area [0..1 ha/kg, R] as function of devel. stage [0..2, R]

*         DVS  SLA    (maximum 15 records)
  SLATB =
           0.00  0.0035
           1.00  0.0016
           2.00  0.0016
* End of Table
********************************************************************************************

********************************************************************************************
* Part 5: Assimilation

  KDIF   =    0.60 ! Extinction coefficient for diffuse visible light, [0..2 -, R]
  KDIR   =    0.60 ! Extinction coefficient for direct visible light, [0..2 -, R]
  EFF    =    0.50 ! Light use efficiency for real leaf [0..10 kg CO2 /J adsorbed), R]
*
* List max CO2 assimilation rate [0..100 kg/ha/hr, R] as function of development stage [0..2 -, R]
*          DVS    AMAX    (maximum 15 records)
  AMAXTB =
           0.00  70.00
           1.25  70.00
           1.50  63.00
           1.75  49.00
           2.00   0.00
* End of table

* List reduction factor of AMAX [-, R] as function of average day temp. [-10..50 C, R]

*          TAVD   TMPF  (maximum 15 records)
  TMPFTB =
           0.00  0.00
           6.00  0.00
          30.00  1.00
          42.00  1.00
          50.00  0.00
* End of table

* List reduction factor of AMAX [-, R] as function of minimum day temp. [-10..50 C, R]

*          TMNR    TMNF  (maximum 15 records)
  TMNFTB =
           5.00  0.000
          12.00  1.000
* End of table
********************************************************************************************

********************************************************************************************
* Part 6: Conversion of assimilates into biomass
*
  CVL    =  0.720 ! Efficiency of conversion into leaves,         [0..1 kg/kg, R]
  CVO    =  0.720 ! Efficiency of conversion into storage organs, [0..1 kg/kg, R]
  CVR    =  0.720 ! Efficiency of conversion into roots,          [0..1 kg/kg, R]
  CVS    =  0.690 ! Efficiency of conversion into stems,          [0..1 kg/kg, R]
********************************************************************************************
```

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**********************************************************************************************
* Part 7: Maintenance respiration
*
  Q10     =  2.0000 ! Rel. increase in respiration rate with temperature, [0..5 /10 C, R]
  RML     =  0.0300 ! Rel. maintenance respiration rate of leaves,  [0..1 kgCH2O/kg/d, R]
  RMO     =  0.0100 ! Rel. maintenance respiration rate of st. org.,[0..1 kgCH2O/kg/d, R]
  RMR     =  0.0100 ! Rel. maintenance respiration rate of roots,   [0..1 kgCH2O/kg/d, R]
  RMS     =  0.0150 ! Rel. maintenance respiration rate of stems,   [0..1 kgCH2O/kg/d, R]

* List reduction factor of senescence [-, R] as function of dev. stage [0..2 -, R]

*          DVS    RFSE   (maximum 15 records)
  RFSETB =
           0.00   1.00
           2.00   1.00
* End of table
**********************************************************************************************


**********************************************************************************************
* Part 8: Partitioning

* List fraction of total dry matter increase partitioned to the roots [kg/kg, R]
* as function of development stage [0..2 -, R]
*          DVS     FR    (maximum 15 records)
  FRTB =
           0.00   0.40
           1.10   0.00
           2.00   0.00
* End of table

* List fraction of total above ground dry matter incr. part. to the leaves [kg/kg, R]
* as function of development stage [0..2 -, R]

*          DVS     FL   (maximum 15 records)
  FLTB =
           0.00   0.62
           0.48   0.62
           0.90   0.28
           1.25   0.00
           1.37   0.00
           2.00   0.00
* End of table

* List fraction of total above ground dry matter incr. part. to the stems [kg/kg, R]
* as function of development stage [0..2 -, R]

*          DVS    FS   (maximum 15 records)
  FSTB =
           0.00   0.38
           0.48   0.38
           0.90   0.72
           1.25   0.24
           1.37   0.00
           2.00   0.00
* End of table

* List fraction of total above ground dry matter incr. part. to the st. organs [kg/kg, R]
* as function of development stage [0..2 -, R]

*          DVS    FO    (maximum 15 records)
  FOTB =
           0.00   0.00
           0.48   0.00
           0.90   0.00
           1.25   0.76
           1.37   1.00
           2.00   1.00
* End of table
**********************************************************************************************
```

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******************************************************************************************
* Part 9: Death rates

  PERDL =   0.030 ! Maximum rel. death rate of leaves due to water stress [0..3 /d, R]

* List relative death rates of roots [kg/kg/d] as function of dev. stage [0..2 -, R]
*          DVS     RDRR     (maximum 15 records)
  RDRRTB =
          0.0000  0.0000
          1.5000  0.0000
          1.5001  0.0200
          2.0000  0.0200
* End of table

* List relative death rates of stems [kg/kg/d] as function of dev. stage [0..2 -, R]
*          DVS      RDRS     (maximum 15 records)
  RDRSTB =
          0.0000  0.0000
          1.5000  0.0000
          1.5001  0.0200
          2.0000  0.0200
* End of table
******************************************************************************************


******************************************************************************************
* Part 10: Crop water use
  swroottyp = 1      ! Switch for type root water extraction  [1,2 -, I]
*                    ! (1 = Feddes et al., 1978; 2 = De Jong van Lier et al., 2006)
* if swroottyp=1 then enter HLIM1 - ADCRL
* if swroottyp=2 then enter wiltpoint, rootradius, rootcoefa
*
*
  HLIM1  =     -10.0 ! No water extraction at higher pressure heads, [-100..100 cm, R]
  HLIM2U =     -25.0 ! h below which optimum water extr. starts for top layer, [-1000..100 cm, R]
  HLIM2L =     -25.0 ! h below which optimum water extr. starts for sub layer, [-1000..100 cm, R]
  HLIM3H =    -400.0 ! h below which water uptake red. starts at high Tpot, [-10000..100 cm, R]
  HLIM3L =    -500.0 ! h below which water uptake red. starts at low Tpot, [-10000..100 cm, R]
  HLIM4  =  -10000.0 ! No water extraction at lower pressure heads, [-16000..100 cm, R]
  ADCRH  =       0.5 ! Level of high atmospheric demand, [0..5 cm/d, R]
  ADCRL  =       0.1 ! Level of low atmospheric demand,  [0..5 cm/d, R]
******************************************************************************************


******************************************************************************************
* Part 11: salt stress

* only when solutes are simulated (SWSOLU=1 in SWP-file)

* relation between ECsat and crop reduction
  ECMAX  =       1.8 ! ECsat level at which salt stress starts, [0..20 dS/m, R]
  ECSLOP =       7.4 ! Decline of rootwater uptake above ECMAX [0..40 %/dS/m, R]

* relation between concentration and ECsat
  C2ECa  =     4.21  ! coefficient a to convert concentration to EC [0.0..1000.0 -, R]
  C2ECb  =     0.763 ! exponent b to convert concentration to EC [0.0..10.0 -, R]
* Switch to enter factor f (SWC2ECF ) per profile or per soil layer/horizon [1,2 -, I]
*    if SWC2ECF = 1 then enter one C2ECf-value for whole model profile
*    if SWC2ECF = 2 then enter one C2ECf-value for each model/soil layer/horizon
  SWC2ECF = 1
* factor f to convert concentration to EC [0.0..10.0 -, R];
*    dependent on SWC2ECF one value for model profile or a value for each soil horizon
  C2ECf  = 1.7
******************************************************************************************


******************************************************************************************
* Section 12: Interception
*
  COFAB  =      0.25 ! Interception coefficient Von Hoyningen-Hune and Braden, [0..1 cm, R]
```

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**********************************************************************************************

**********************************************************************************************
* Part 13: Root density distribution and root growth
*
* List relative root density [0..1 -, R], as function of rel. rooting depth [0..1 -, R]:
*         RD     RDC    (maximum 11 records)
  RDCTB =
          0.00   1.00
          1.00   1.00
* End of table
*
  RDI    =   10.00 ! Initial rooting depth, [0..1000 cm, R]
  RRI    =    1.20 ! Maximum daily increase in rooting depth, [0..100 cm/d, R]
  RDC    =   75.00 ! Maximum rooting depth crop/cultivar, [0..1000 cm, R]
*
**********************************************************************************


*** IRRIGATION SCHEDULING SECTION ***

**********************************************************************************
* Part 1: General

  SCHEDULE = 0  ! Switch for application irrigation scheduling [Y=1, N=0]

* If SCHEDULE = 0, no more information is required in this input file!
* If SCHEDULE = 1, continue ....

  STARTIRR = 30 3 ! Specify day and month after which irrigation scheduling is allowed [dd mm]
  ENDIRR = 31 12  ! Specify day and month after which irrigation scheduling is NOT allowed [dd mm]
  CIRRS = 0.0     ! solute concentration of scheduled irrig. water, [0..100 mg/cm3, R]
  ISUAS = 1       ! Switch for type of irrigation method:
                  ! 0 = sprinkling irrigation
                  ! 1 = surface irrigation

* Specify pressure head at field capacity
* required for timing options  TCS = 2, 3, or 4 and depth option DCS = 1, else dummy
  phFieldCapacity = -100.0   ! soil hydraulic pressure head [-1000.0 .. 0.0,cm, R]

**********************************************************************************


**********************************************************************************
* Part 2: Irrigation time criteria

*** Choose one of the following 5 timing options:
  TCS = 1  ! Switch, timing criterion  [1..6, I]]
!           TCS = 1   :  Daily Stress
!           TCS = 2   :  Depletion of Readily Available Water
!           TCS = 3   :  Depletion of Totally Available Water
!           TCS = 4   :  Depletion Water Amount
!           TCS = 5   :  Pressure head or moisture content
!           TCS = 6   :  Fixed weekly irrigation, rootzone to field capacity


*** Daily stress criterion (TCS = 1)
* If TCS = 1, specify mimimum of ratio actual/potential transpiration Trel [0..1, R],
* as function of development stage DVS_tc1 [0..2, R], maximum 7 records:
  DVS_tc1  Trel
      0.0  0.95
      2.0  0.95
* End of table


*** Depletion of Readily Available Water (TCS = 2)
* If TCS = 2, specify minimal fraction of readily available water RAW [0..1, R],
* as function of development stage DVS_tc2 [0..2, R], maximum 7 records:
  DVS_tc2   RAW
```

```
      0.0  0.95
      2.0  0.95
* End of table


*** Depletion of Totally Available Water (TCS = 3)
* If TCS = 3, specify minimal fraction of totally available water TAW [0..1, R],
* as function of development stage DVS_tc3 [0..2, R], maximum 7 records:
  DVS_tc3   TAW
      0.0  0.50
      2.0  0.50
* End of table


*** Depletion Water Amount (TCS = 4)
* If TCS = 4, specify maximum amount of water depleted below field cap. DWA [0..500 mm, R],
* as function of development stage DVS_tc4 [0..2, R], maximum 7 records:
  DVS_tc4   DWA
      0.0  40.0
      2.0  40.0
* End of table


*** Pressure head or Moisture content (TCS = 5)
* If TCS = 5, specify:
  PHORMC = 0   ! Switch, use pressure head (PHORMC=0) or water content (PHORMC=1)
  DCRIT = -30.0! Depth of the sensor [-100..0 cm, R]
* Also specify critical pressure head [-1.d6..-100 cm, R] or moisture content
* [0..1.0 cm3/cm3, R], as function of development stage DVS_tc5 [0..2, R]:
  DVS_tc5  Value_tc5
      0.0    -1000.0
      2.0    -1000.0
* End of table


*** Fixed weekly irrigation, rootzone to field capacity (TCS = 6)
* If TCS = 6, specify:
* Threshold for weekly irrigation; only irrigate when deficit is higher than threshold
  irgthreshold = 1.0       ! threshold value  [0.0..20.0 mm, R]


*** Select (optional) fixed time interval:
  tcsfix = 0  ! Switch, fixed timing criterion  [0 or 1, I]]
* If tcsfix = 1, specify:
  irgdayfix = 7    !   length of interval (number of days) [1..365, I]

**********************************************************************************


**********************************************************************************
* Part 3: Irrigation depth criteria

*** Choose one of the following 2 options for irrigation depth:
* Next line is required for Swap303 - swap3177
  DCS = 1      ! Switch, depth criterion  [1..2, I]]
!                DCS = 1 :  Back to Field Capacity
!                DCS = 2 :  Fixed Irrigation Depth


*** Back to Field Capacity (DCS = 1)
* If DCS = 1, specify amount of under (-) or over (+) irrigation dI [-100..100 mm, R],
* as function of development stage DVS_dc1 [0..2, R], maximum 7 records:
  DVS_dc1   dI
     0.0  10.0
     2.0  10.0
* End of table


*** Fixed Irrigation Depth (DCS = 2)
* If DCS = 2, specify fixed irrigation depth FID [0..400 mm, R],
```

```
* as function of development stage DVS_dc2 [0..2, R], maximum 7 records:
  DVS_dc2   FID
      0.0  60.0
      2.0  60.0
* End of table


*** Select (optional) limitations of irrigation depth:
  dcslim = 0  ! Switch, limited irrigation depth  [0=No, 1=Yes]   [0..1, I]
* If dcslim = 1, specify:
  irgdepmin = 0.0    !   minimum irrigation depth [0.0d0 .. 100.0d0, mm, I]
  irgdepmax = 0.0    !   maximum irrigation depth [irgdepmin .. 1.0d7, mm, I]


* End of .crp file !
```

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**********************************************************************************
* Filename: webster.DRA
* Contents: SWAP 3.2 - Input data for basic and extended drainage
**********************************************************************************
* Comment area:
* Case: Iowa's tile landscape
*
**********************************************************************************


*** BASIC DRAINAGE SECTION ***

**********************************************************************************
* Part 0: General

  DRAMET = 2 ! Switch, method of lateral drainage calculation:
*              METHOD 1 = Use table of drainage flux - groundwater level relation
*              METHOD 2 = Use drainage formula of Hooghoudt or Ernst
*              METHOD 3 = Use drainage/infiltration resistance, multi-level if needed

  SWDIVD = 1 ! Calculate vertical distribution of drainage flux in groundwater [Y=1, N=0]

* If SWDIVD = 1, specify anisotropy factor COFANI (horizontal/vertical saturated hydraulic
* conductivity) for each soil layer (maximum MAHO), [0..1000 -, R] :
  COFANI =    1.0    1.0

* Switch to adjust upper boundary of model discharge laye
  SWDISLAY = 0                 ! switch to adjust discharge layer  [0,1,2, -, I]
*
* If SWDISLAY = 1, specify for the drainage systems 1 - NRLEVS or NRSRF:
*  - swtopdislay(madr)  ! Switch, for each drainage level, to distribute drainage
*                         flux vertically with a given position of the top of the
*                         model discharge layers: [0,1 - , I]   0 = no; 1 = yes
*  - ztopdislay(madr)   ! Array with depth of top of model discharge layer for
*                         each drain level, see also swtopdislay (L);
* If SWDISLAY = 2, then specify ftopdislay instead of ztopdislay:
*  - ftopdislay(madr)   ! Array with factor of top of model discharge layer for
*                         each drain level, see also swtopdislay ();

*  (level is a dummy array, just as either ztopdislay or ftopdislay)
 level  swtopdislay  ztopdislay  ftopdislay
   1        1           -200.0      0.5
   2        0           -0.01       0.0
* end of SWDISLAY-tabel
**********************************************************************************


**********************************************************************************
* METHOD 1 - Part 1: Table of drainage flux - groundwater level relation (DRAMET = 1)

* If SWDIVD = 1, specify the drain spacing:
  LM1 = 30.  ! Drain spacing, [1..1000 m, R]

* Specify drainage flux Qdrain [-100..1000 cm/d, R] as function of groundwater level
* GWL [-1000.0..10.0 cm, R, negative below soil surface]; maximum of 25 records
* start with highest groundwater level:

     GWL     Qdrain
   -20.0        0.5
   -100.        0.1
* End of table
**********************************************************************************


**********************************************************************************
* METHOD 2 - Part 2: Drainage formula of Hooghoudt or Ernst (DRAMET = 2)

* Drain characteristics:
  LM2    = 25.0     ! Drain spacing, [1..1000 m, R]
```

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  SHAPE = 0.8       ! Shape factor to account for actual location between drain and water divide
[0.0..1.0 -, R]
  WETPER =  9.425   ! Wet perimeter of the drain,  [0..1000 cm, R]
  ZBOTDR = -106.0   ! Level of drain bottom, [-1000..0 cm, R, neg. below soil surface]
  ENTRES =  0.46    ! Drain entry resistance, [0..1000 d, R]

* Soil profile characteristics:

  IPOS = 2   ! Switch for position of drain:
*              1 = On top of an impervious layer in a homogeneous profile
*              2 = Above an impervious layer in a homogeneous profile
*              3 = At the interface of a fine upper and a coarse lower soil layer
*              4 = In the lower, more coarse soil layer
*              5 = In the upper, more fine soil layer

* For all positions specify:
  BASEGW = -390.    ! Level of impervious layer, [-1d4..0 cm, R]
  KHTOP  =  20.66   ! Horizontal hydraulic conductivity top layer, [0..1000 cm/d, R]

* In addition, in case IPOS = 3,4,5
  KHBOT  =  10.0    ! horizontal hydraulic conductivity bottom layer, [0..1000 cm/d, R]
  ZINTF  = -150.    ! Level of interface of fine and coarse soil layer, [-1d4..0 cm, R]

* In addition, in case IPOS = 4,5
  KVTOP  =   5.0    ! Vertical hydraulic conductivity top layer, [0..1000 cm/d, R]
  KVBOT  =  10.0    ! Vertical hydraulic conductivity bottom layer, [0..1000 cm/d, R]

* In addition, in case IPOS = 5
  GEOFAC =  4.8     ! Geometry factor of Ernst,  [0..100 -, R]
**********************************************************************************


**********************************************************************************
* METHOD 3 - Part 3: Drainage and infiltration resistance (DRAMET = 3)

  NRLEVS = 2        ! Number of drainage levels, [1..5, I]

* Option for interflow in highest drainage level (shallow system with short residence time)
  SWINTFL = 0       ! Switch for interflow [0,1, I]

* If SWINTFL = 1, specify:
  COFINTFLB = 0.5   ! Coefficient for interflow relation  [0.01..10.0 d, R]
  EXPINTFLB = 1.0   ! Exponent for interflow relation  [0.1..1.0 -, R]


* Switch to adjust the bottom of the model discharge layer; only
* in case of lateral (swdivdra=1) interflow or rapid drainage (Swnrsrf=1 or Swnrsrf=2).
* When the switch is on (SwTopnrsrf=1) then the bottom of the highest order drainage
* system (Zbotdr(NumDrain)) represents the max depth of the interflow.
 SwTopnrsrf = 0 ! Switch to enable adjustment of model discharge layer [0,1, I]
**********************************************************************************


**********************************************************************************
* Part 3a: Drainage to level 1

  DRARES1 = 100   ! Drainage resistance, [10..1d5 d, R]
  INFRES1 = 100   ! Infiltration resistance, [0..1d5 d, R]
  SWALLO1 =   1   ! Switch, for allowance drainage/infiltration:
                  ! 1 = Drainage and infiltration are both allowed
                  ! 2 = Drainage is not allowed
                  ! 3 = Infiltration is not allowed

* If SWDIVD = 1 (drainage flux vertically distributed), specify the drain spacing:
  L1    = 20.     ! Drain spacing, [1..1000 m, R]

  ZBOTDR1 = -90.0 ! Level of drainage medium bottom, [-1000..0 cm, R]
  SWDTYP1 = 2     ! Type of drainage medium: 1 = drain tube, 2 = open channel

* In case of open channel (SWDTYP1 = 2), specify date DATOWL1 [dd-mmm-yyyy] and channel
```

```
* water level LEVEL1 [cm, negative if below soil surface], maximum MAOWL records:

       DATOWL1   LEVEL1
   01-may-1982    -90.0
   30-may-1982    -90.0
* End of table
**********************************************************************************


**********************************************************************************
* Part 3b: Drainage to level 2

  DRARES2 = 100   ! Drainage resistance, [10..1E5 d, R]
  INFRES2 = 100   ! Infiltration resistance, [0..1E5 d, R]
  SWALLO2 =   1   ! Switch, for allowance drainage/infiltration:
                  ! 1 = Drainage and infiltration are both allowed
                  ! 2 = Drainage is not allowed
                  ! 3 = Infiltration is not allowed

* If SWDIVD = 1 (drainage flux vertically distributed), specify the drain spacing:
  L2 = 20.        ! Drain spacing, [1..1000 m, R]

  ZBOTDR2 = -90.0 ! Level of drainage medium bottom, [-1000..0 cm, R]
  SWDTYP2 = 2     ! Type of drainage medium: 1 = drain tube, 2 = open channel

* In case of open channel (SWDTYP2 = 2), specify date DATOWL2 [dd-mmm-yyyy] and channel
* water level LEVEL2 [cm, negative if below soil surface], maximum MAOWL records:

       DATOWL2   LEVEL2
   01-may-1982    -90.0
   30-may-1982    -90.0
* End of table
**********************************************************************************


**********************************************************************************
* Part 3c: Drainage to level 3

  DRARES3 = 100   ! Drainage resistance, [10..1E5 d, R]
  INFRES3 = 100   ! Infiltration resistance, [0..1E5 d, R]
  SWALLO3 =   1   ! Switch, for allowance drainage/infiltration:
                  ! 1 = Drainage and infiltration are both allowed
                  ! 2 = Drainage is not allowed
                  ! 3 = Infiltration is not allowed

* If SWDIVD = 1 (drainage flux vertically distributed), specify the drain spacing:
  L3 = 20.        ! Drain spacing, [1..1000 m, R]

  ZBOTDR3 = -90.0 ! Level of drainage medium bottom, [-1000..0 cm, R]
  SWDTYP3 = 2     ! Type of drainage medium: 1 = drain tube, 2 = open channel

* In case of open channel (SWDTYP3 = 2), specify date DATOWL3 [dd-mmm-yyyy] and channel
* water level LEVEL3 [cm, negative if below soil surface], maximum MAOWL records:

       DATOWL3   LEVEL3
   01-may-1982    -90.0
   30-may-1982    -90.0
* End of table
**********************************************************************************


**********************************************************************************
* Part 3d: Drainage to level 4

  DRARES4 = 100   ! Drainage resistance, [10..1E5 d, R]
  INFRES4 = 100   ! Infiltration resistance, [0..1E5 d, R]
  SWALLO4 =   1   ! Switch, for allowance drainage/infiltration:
                  ! 1 = Drainage and infiltration are both allowed
                  ! 2 = Drainage is not allowed
                  ! 3 = Infiltration is not allowed
```

```
* If SWDIVD = 1 (drainage flux vertically distributed), specify the drain spacing:
  L4 = 20.        ! Drain spacing, [1..1000 m, R]

  ZBOTDR4 = -90.0 ! Level of drainage medium bottom, [-1000..0 cm, R]
  SWDTYP4 = 2     ! Type of drainage medium: 1 = drain tube, 2 = open channel

* In case of open channel (SWDTYP4 = 2), specify date DATOWL4 [dd-mmm-yyyy] and channel
* water level LEVEL4 [cm, negative if below soil surface], maximum MAOWL records:

       DATOWL4   LEVEL4
   01-may-1982    -90.0
   30-may-1982    -90.0
* End of table
**********************************************************************************


**********************************************************************************
* Part 3e: Drainage to level 5

  DRARES5 = 100   ! Drainage resistance, [10..1E5 d, R]
  INFRES5 = 100   ! Infiltration resistance, [0..1E5 d, R]
  SWALLO5 =   1   ! Switch, for allowance drainage/infiltration:
                  ! 1 = Drainage and infiltration are both allowed
                  ! 2 = Drainage is not allowed
                  ! 3 = Infiltration is not allowed

* If SWDIVD = 1 (drainage flux vertically distributed), specify the drain spacing:
  L5 = 20.        ! Drain spacing, [1..1000 m, R]

  ZBOTDR5 = -90.0 ! Level of drainage medium bottom, [-1000..0 cm, R]
  SWDTYP5 = 2     ! Type of drainage medium: 1 = drain tube, 2 = open channel

* In case of open channel (SWDTYP5 = 2), specify date DATOWL5 [dd-mmm-yyyy] and channel
* water level LEVEL5 [cm, negative if below soil surface], maximum MAOWL records:

       DATOWL5   LEVEL5
   01-may-1982    -90.0
   30-may-1982    -90.0
* End of table
***********************************************************************************


*** EXTENDED DRAINAGE SECTION ***

********************************************************************************
* Part 0: Reference level

 ALTCU = 0.0 ! ALTitude of the Control Unit relative to reference level
*                 AltCu = 0.0 means reference level coincides with
*                 surface level [-300000..300000 cm, R]

********************************************************************************
* Part 1a: drainage characteristics
*
 NRSRF  = 1    ! number of subsurface drainage levels [1..5, I]
*
*** Table with physical characteristics of each subsurface drainage level:
*
* LEVEL   ! drainage level number [1..NRSRF, I]
* SWDTYP  ! type of drainage medium [open=0, closed=1]
* L       ! spacing between channels/drains [1..1000 m, R]
* ZBOTDRE ! altitude of bottom of channel or drain [ALTCU-1000..ALTCU-0.01 cm,R]
* GWLINF  ! groundw. level for max. infiltr. [-1000..0 cm rel. to soil surf., R]
* RDRAIN  ! drainage resistance [1..100000 d, R]
* RINFI   ! infiltration resistance  [1..100000 d, R]
* Variables RENTRY, REXIT, WIDTHR and TALUDR must have realistic values when the
*          type of drainage medium is open (second column of this table:SWDTYP=0)
*          For closed pipe drains (SWDTYP=1) dummy values may be entered
* RENTRY  ! entry resistance  [1..100 d, R]
```

```
* REXIT   ! exit resistance   [1..100 d, R]
* WIDTHR  ! bottom width of channel [0..100 cm, R]
* TALUDR  ! side-slope (dh/dw) of channel [0.01..5, R]
*
 LEV SWDTYP    L   ZBOTDRE GWLINF RDRAIN RINFI RENTRY REXIT  WIDTHR TALUDR
  1   1      7.6   390.0  -350.0 150.0  4000.0  0.8    0.8  100.0  0.66
* End_of_table
********************************************************************************

********************************************************************************
* Part 1b: Separate criteria for highest (shallow) drainage system
*
 SWNRSRF = 0     ! Switch to introduce rapid subsurface drainage [0..2, I]
*            0 = no rapid drainage
*            1 = rapid drainage in the highest drainage system (=NRSRF)
*                (implies adjustment of RDRAIN of highest drainage system)
*            2 = rapid drainage as interflow according to a power relation
*                (implies adjustment of RDRAIN of highest drainage system)
* When SWRNSRF = 1, then enter realistic values for rapid drainage
 RSURFDEEP    = 30.0   ! maximum resistance of rapid subsurface Drainage [0.001..1000.0 d, R]
 RSURFSHALLOW = 10.0   ! minimum resistance of Rapid subsurface Drainage [0.001..1000.0 d, R]
*
* When SWRNSRF = 2, then enter coefficients of power function
 COFINTFL = 0.1        ! coefficient of interflow relation [0.01..10.0 d-1, R]
 EXPINTFL = 0.5        ! exponent of interflow relation [0.1...1.0 -, R]
*
*
********************************************************************************
* Part 2a: Specification and control of surface water system
*
 SWSRF = 1 ! option for interaction with surface water system [1..3, I]
*            1 = no interaction with surface water system
*            2 = surf. water system is simulated with no separate primary system
*            3 = surf. water system is simulated with separate primary system
********************************************************************************
*
********************************************************************************
* Part 2b: Surface water level of primary system
*
* Only if SWSRF = 3 then the following table must be entered
* Table with Water Levels in the Primary system [max. = 52]:
* no levels above soil surface for primary system
*
* Water level in primary water course WLP [ALTCU-1000..ALTCU-0.01 cm, R] as function of
* DATE1 [dd-mmm-yyyy]

      DATE1      WLP
 01-mar-1982    -100.
 15-mar-1982     -80.
 30-mar-1982    -120.
*End_of_table
********************************************************************************
*
********************************************************************************
* Part 2c: Surface water level of secondary system

* If SWSRF =  2 or 3  then the variable SWSEC must be entered

 SWSEC = 2 ! option for surface water level of secondary system [1..2, I]
*            1 = surface water level is input
*            2 = surface water level is simulated
********************************************************************************

********************************************************************************
* Part 3: surface water level in secondary water course is input
*
* Table with Water Levels in the Secondary system [max. = 52]:
*
* Water level in secondary water course WLS [ALTCU-1000..ALTCU-0.01 cm, R] as function of
* DATE2 [dd-mmm-yyyy]
```

```
      DATE2      WLS
 01-may-1982    -100.
 15-may-1982     -80.
 30-may-1982    -120.
*End_of_table
********************************************************************************

********************************************************************************
* Part 4: surface water level is simulated
*
********************************************************************************
* Part 4a: Miscellaneous parameters
*
 WLACT  = 1123.0 ! initial surface water level [ALTCU-1000..ALTCU cm,R]
 OSSWLM =   2.5  ! criterium for warning about oscillation [0..10 cm, R]
********************************************************************************
*
********************************************************************************
* Part 4b: management of surface water levels
*
 NMPER  =  4    ! number of management periods [1..10, I]
*
* For each management period specify:
* IMPER  index of management period [1..NMPER, I]
* IMPEND date that period ends [dd-mm-yyyy]
* SWMAN  type of water management [1..2, I]
*        1 = fixed weir crest
*        2 = automatic weir
* WSCAP  surface water supply capacity [0..100 cm/d, R]
* WLDIP  allowed dip of surf. water level, before starting supply [0..100 cm, R]
* INTWL  length of water-level adjustment period (SWMAN=2 only) [1..31 d, R]

 IMPER_4b          IMPEND    SWMAN   WSCAP   WLDIP   INTWL
       1     01-mar-1982       1     0.00     0.0       1
       2     10-mar-1982       2     0.00     5.0       1
       3     20-mar-1982       2     0.00     5.0       1
       4     30-mar-1982       1     0.00     0.0       1
*End_of_table
*
 SWQHR  = 1 ! option for type of discharge relationship [1..2, I]
*            1 = exponential relationship
*            2 = table
********************************************************************************
*
********************************************************************************
* Part 4c: exponential discharge relation (weir characteristics)
*
* If SWQHR=1 and for ALL periods specify:
*
 SOFCU = 100.0  ! Size of the control unit [0.1..100000.0 ha, R]
*
* IMPER  index of management period [1..NMPER, I]
* HBWEIR weir crest; levels above soil surface are allowed, but simulated
*        surface water levels should remain below 100 cm above soil surface;
*        the crest must be higher than the deepest channel bottom of the
*        secondary system (ZBOTDR(1 or 2),  [ALTCU-ZBOTDR..ALTCU+100 cm,R].
*        If SWMAN = 2: HBWEIR represents the lowest possible weir position.
* ALPHAW alpha-coefficient of discharge formula [0.1..50.0, R]
* BETAW  beta-coefficient of discharge formula [0.5..3.0, R]

 IMPER_4c  HBWEIR  ALPHAW   BETAW
     1    1114.0    3.0    1.4765
     2    1110.0    3.0    1.4765
     3    1110.0    3.0    1.4765
     4    1114.0    3.0    1.4765
*End_of_table
********************************************************************************
*
********************************************************************************
```

```
* Part 4d: table discharge relation
*
* If SWQHR=2 and for ALL periods specify:
*
* IMPER  index of management period [1..NMPER, I]
* ITAB   index per management period [1..10, I]
* HTAB   surface water level [ALTCU-1000..ALTCU+100 cm, R]
*        (first value for each period = ALTCU + 100 cm)
* QTAB   discharge [0..500 cm/d, R]
*        (should go down to a value of zero at a level that is higher than
*        the deepest channel bottom of secondary surface water system)
*
 IMPER_4d IMPTAB  HTAB    QTAB
    1       1      100.0   2.0
    1       2        0.0   1.0
    1       3     -100.0   0.5
    1       4     -185.0   0.0
*End_of_table
********************************************************************************
*
********************************************************************************
* Part 4e: automatic weir control
*
* For the periods when SWMAN=2 specify next two tables:
*
*** Table #1
*
*
* IMPER  index of management period [1..NMPER, I]
* DROPR  maximum drop rate of surface water level [0..100 cm/d, positive, R]
*        if the value is set to zero, the parameter does not play
*        any role at all
* HDEPTH depth in soil profile for comparing with HCRIT
*        [-100..0 cm below soil surface, R]
*
 IMPER_4E1 DROPR   HDEPTH
       2    0.0     -15.0
       3    0.0     -15.0
*End_of_table
*
*** Table #2
*
* IMPER   index of management period [1..NMPER, I]
* IPHASE  index per management period [1..10, I]
* WLSMAN  surface water level of phase IPHASE [ALTCU-500.0..ALTCU cm,R]
* GWLCRIT groundwater level of phase IPHASE,  max. value
*         [-500..0 cm  below soil surface, R]
* HCRIT   critical pressure head, max. value, (at HDEPTH, see above)
*         for allowing surface water level [-1000..0 cm, neg., R]
* VCRIT   critical unsaturated volume (min. value) for all
*         surface water level [0..20 cm, R]
*
*   Notes: 1) The zero's for the criteria on the first record are in fact
*             dummy's, because under all circumstances the scheme will set
*             the surface water level at least to wlsman(imper,1)
*          2) The lowest level of the scheme must still be above the
*             deepest channel bottom of the secondary surface water system
*
 IMPER_4E2 IMPPHASE WLSMAN GWLCRIT    HCRIT   VCRIT
         2     1    1114.0     0.0      0.0     0.0
         2     2    1124.0   -80.0      0.0     0.0
         2     3    1124.0   -90.0      0.0     0.0
         2     4    1154.0  -100.0      0.0     0.0
         3     1    1114.0     0.0      0.0     0.0
         3     2    1124.0   -80.0      0.0     0.0
         3     3    1124.0   -90.0      0.0     0.0
         3     4    1154.0  -100.0      0.0     0.0
*End_of_table
********************************************************************************
End of .dra file!
```

```
*****************************************************************************************************
* File Name: amesdetail.987
* Contents: SWAP - Detailed meteorological data of Ames, IA
*****************************************************************************************************
* Comment Area:
* Records taken to evaluate weather in Ames from 1987 - 2012 (26 years)
* Data found on {http://mesonet.agron.iastate.edu/agclimate/hist/hourlyRequest.php} for Ames weather
station.
*****************************************************************************************************
```

Date	Record	Rad	Temp	Hum	Wind	Rain
*d-mon-year	nr	kJ/m2	C	kPa	m/s	mm
01-Jan-1987	1	0.0	-0.3	0.49	0.5	0.0
01-Jan-1987	2	0.0	-0.4	0.49	0.5	0.0
01-Jan-1987	3	0.0	-0.4	0.48	0.5	0.0
01-Jan-1987	4	0.0	-0.4	0.48	0.5	0.0
01-Jan-1987	5	0.0	-0.3	0.47	0.5	0.0
01-Jan-1987	6	0.0	-0.4	0.45	0.5	0.0
01-Jan-1987	7	0.0	-0.4	0.46	0.5	0.0
01-Jan-1987	8	0.0	-0.4	0.48	0.5	0.0
01-Jan-1987	9	0.0	-0.5	0.48	0.5	0.0
01-Jan-1987	10	180.6	-0.5	0.48	0.5	0.0
01-Jan-1987	11	417.8	-0.5	0.47	0.5	0.0
01-Jan-1987	12	723.1	-0.5	0.46	0.5	0.0
01-Jan-1987	13	697.5	-0.5	0.44	0.5	0.0
01-Jan-1987	14	913.6	-0.5	0.41	0.5	0.0
01-Jan-1987	15	712.9	-0.4	0.40	0.5	0.0
01-Jan-1987	16	518.1	-0.5	0.40	0.5	0.0
01-Jan-1987	17	258.0	-0.4	0.40	0.5	0.0
01-Jan-1987	18	21.9	-0.5	0.42	0.5	0.0
01-Jan-1987	19	0.0	-0.4	0.45	0.5	0.0
01-Jan-1987	20	0.0	-0.4	0.47	0.5	0.0
01-Jan-1987	21	0.0	-0.4	0.48	0.5	0.0
01-Jan-1987	22	0.0	-0.5	0.48	0.5	0.0
01-Jan-1987	23	0.0	-0.5	0.48	0.5	0.0
01-Jan-1987	24	0.0	-0.5	0.48	0.5	0.0
02-Jan-1987	1	0.0	-0.6	0.48	0.5	0.0
02-Jan-1987	2	0.0	-0.6	0.48	0.5	0.0
02-Jan-1987	3	0.0	-0.7	0.48	0.5	0.0
02-Jan-1987	4	0.0	-0.7	0.48	0.5	0.0
02-Jan-1987	5	0.0	-0.8	0.48	0.5	0.0
02-Jan-1987	6	0.0	-0.8	0.48	0.5	0.0
02-Jan-1987	7	0.0	-0.8	0.48	0.5	0.0
02-Jan-1987	8	0.0	-0.9	0.48	0.5	0.0
02-Jan-1987	9	0.0	-0.9	0.48	0.5	0.0
02-Jan-1987	10	217.6	-0.9	0.48	0.5	0.0
02-Jan-1987	11	390.0	-0.9	0.47	0.5	0.0
02-Jan-1987	12	834.9	-0.9	0.46	0.5	0.0
02-Jan-1987	13	1120.4	-1.0	0.42	0.5	0.0
02-Jan-1987	14	1431.1	-0.7	0.36	0.5	0.0
02-Jan-1987	15	1207.6	-0.7	0.36	0.5	0.0
02-Jan-1987	16	841.6	-0.7	0.35	0.5	0.0
02-Jan-1987	17	457.9	-0.7	0.35	0.5	0.0
02-Jan-1987	18	70.6	-0.7	0.38	0.5	0.0
02-Jan-1987	19	0.0	-0.6	0.43	0.5	0.0
02-Jan-1987	20	0.0	-0.6	0.49	0.5	0.0
02-Jan-1987	21	0.0	-0.6	0.51	0.5	0.0
02-Jan-1987	22	0.0	-1.2	0.51	0.5	0.0
02-Jan-1987	23	0.0	-1.2	0.51	0.5	0.0
02-Jan-1987	24	0.0	-1.2	0.51	0.5	0.0
03-Jan-1987	1	0.0	-1.2	0.52	0.5	0.0
03-Jan-1987	2	0.0	-1.1	0.52	0.5	0.0
03-Jan-1987	3	0.0	-1.1	0.51	0.5	0.0
03-Jan-1987	4	0.0	-1.2	0.50	0.5	0.0
03-Jan-1987	5	0.0	-1.2	0.50	0.5	0.0
03-Jan-1987	6	0.0	-1.2	0.49	0.5	0.0

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