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Hydrologic impacts of tile drainage in Iowa

Brandon Patrick Sloan
University of Iowa

HYDROLOGIC IMPACTS OF TILE DRAINAGE IN IOWA

by

Brandon Patrick Sloan

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Thesis Supervisor: Adjunct Assistant 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

Brandon Patrick Sloan

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

Thesis Committee: ___________________________________
Nandita Basu, Thesis Supervisor

____
Larry Weber

____
Allen Bradley

____
Ricardo Mantilla

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ABSTRACT

Agricultural tile drainage is an integral part of Iowa's landscape, with nearly 30% of Iowa's cropland being drained (Schilling & Helmers, 2008). Tile drainage allows for efficient crop production in Iowa's nutrient rich soils by removing excess water from frequently inundated fields through subsurface pipe networks. These tile systems are suspected of altering the hydrologic regime of Iowa, but the extent of the problem remains unknown. A literature review is performed to assess the current understanding of tile drainage and to help create a framework of analysis to address this problem. The deterministic field-scale model DRAINMOD is used in both a field and catchment scale analysis of the hydrologic impacts of tile drainage in conditions typical to Iowa. The field-scale study explores the influence of soil type, surface storage, rainfall characteristics, and drainage spacing on how tiling impacts the hydrologic response . A range of metrics, including the mean annual peak flow, flow duration curves, and the Richard Baker Flashiness Index are used for the analysis. Subsurface drainage was observed to have no impact on the mean annual peak flow. This is because the largest storms of the year are almost always dominated by surface runoff, rendering the additional storage created by the tiles inconsequential. Metrics that captured the entire flow regime were, however, affected significantly by tiles. The flashiness index of less permeable soils, typical of Iowa, reduced with tile drainage, due to a change from surface dominated to subsurface dominated flow. The reduction varied spatially as a function of rainfall percentiles, and at 25th percentile rainfall, increases were observed in certain areas. A saddle shaped behavior was observed between tile spacing and flashiness index, demonstrating the existence of an optimal spacing minimizes the effect of drainage. The field scale DRAINMOD results are then used in conjunction with a simplified routing equation to analyze the impact of tile drains on the Clear Creek Watershed (CCW) in Iowa. It was found that adding drained fields to the densest portion of the CCW width

function leads to the greatest reduction of peak flow at the outlet, as long as the percentage of the watershed drained is maintained constant.

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CHAPTER 1: INTRODUCTION

1.1 Motivation

Agricultural tile drainage is an integral part of Iowa's landscape, with nearly 30% of Iowa's cropland being drained (Schilling & Helmers, 2008). Tile drainage allows for efficient crop production in Iowa's nutrient rich soils by removing excess water from frequently inundated fields through subsurface pipe networks. Iowa's livelihood is agriculturally based and has been maintained and strengthened over the past century by tile drains. However, the installation of these pipes into the subsurface has altered the hydrologic and ecological regime. Recent research has focused on minimizing the impact that tile discharge has had on water quality in Iowa's streams and ultimately in the Mississippi River. However, the influence of tile drainage on the hydrologic regime has received less constructive attention. Given the severe floods in Iowa over the past few decades, namely 1993 and 2008, questions are being raised about the source of these catastrophic events. An obvious culprit is tile drainage because many of Iowa's soils require its use in order to reach their agronomic potential (**Figure 3-6**). This is particularly significant in light of the fact that over the past 70 years, soybean cultivation in Iowa has increased 1000%, and row crop production has increased between 30-40% (Schilling & Helmers, 2008).

Unfortunately, there has only been speculation, rather than a definitive explanation, as to why the frequency of these large flooding events has recently increased. The two leading theories on how tile drainage influences flooding are: 1) tile drains remove water that would be stored in the subsurface faster than lateral seepage alone, which causes flooding downstream and 2) tiling allows potential surface runoff to infiltrate and be released at a slower rate, thereby mitigating flooding downstream. Both theories have merit, but neither definitively explains how tile drains impact Iowa's hydrology. The limited research that has been performed on the hydrologic impact of tile drainage has posed many good qualitative relationships, but it ultimately concludes that the impact is a complex interaction of hydrologic processes and is situationally dependent. Furthermore, the majority of research has been performed at the field scale and cannot be easily extrapolated to the catchment scale at which flooding is experienced and analyzed.

There is no clear framework for the current understanding of the hydrologic impacts of tiles at different scales. Without a clear vision of what is known, it is difficult to advance that knowledge. Additionally, there is a need for general conclusions, whether adverse or beneficial, about how tile drainage is affecting Iowa's hydrologic regime. A simple methodology for analyzing the impacts at multiple scales will illuminate the issue and reveal fundamental facts about the impacts of tiles in Iowa.

1.2 Objectives

The overall objective of this study is to expand upon the current base of knowledge by numerically exploring the impacts of tiles at the field (~1 ha) and catchment scales (~260 km^2) while providing an accessible framework for understanding the impacts of tile drainage on hydrology in Iowa. The specific objectives are threefold:

1. Provide an extensive literature review in order to assess the current level of understanding of the hydrologic impacts of tile drainage.
2. Perform numerical simulations to explore the influence of landscape, climatic, and anthropogenic controls on the impact of tiling at the field scale under Iowa conditions.
3. Utilize a simplified catchment scale model to analyze the impacts of drained fields and their location in the watershed on the outlet hydrograph at the 260 km^2 scale.

Chapter 2 focuses on the literature review. The field and catchment scale analyses are located in Chapters 3 and 4, respectively, and the conclusions are found in Chapter 5.

CHAPTER 2: LITERATURE REVIEW OF THE HYDROLOGIC IMPACTS OF TILE DRAINAGE

2.1 Introduction

The hydrologic impacts of tile drainage have been studied since the mid-1800s (Robinson, 1990). Yet, to this day, there is no definitive explanation of what the actual impacts are. Current theories put forth in the literature suggest that the answer depends on pre-drainage soil water conditions, soil type, climate, land use, and topography. However, the majority of studies in the literature were performed at the field scale, and scaling the results in the few existing studies up to larger scales introduces further uncertainties and complexities. The purpose of this literature review is to illustrate the strengths and weaknesses of current conceptions of the impacts of tile drainage. The primary focus is on field scale impacts, since that is what the majority of research covers. There are theories of tiling's impact at the catchment scale, but those will be covered in Chapter 4. The results are broken down into three main categories: Landscape, Climatic , and Anthropogenic Controls.

2.2 Landscape Controls: Soil Type, Macropores, and Presence of Surface Storage

Landscape attributes like soil type, the presence of macropores, and surface storage are among the most dominant factors that control whether the installation of subsurface drainage decreases or increases the peak flow (Blann, Anderson, Sands, & Vondracek, 2009; Robinson, 1990; Schwab, Fausey, Desmond, & Holman, 1985; Skaggs, Breve, & Gilliam, 1994). It has generally been observed that subsurface drainage decreases the peak flow in clayey soils, while it increases the peak flow in sandy soils (Robinson, 1990; Robinson & Rycroft, 1999). One of the most comprehensive studies exploring this effect (Robinson, 1990) involved data collected from six field sites in the United Kingdom (UK) spanning different soil types: three clay soils, one silty loam, and two peat soils (**Table 2-1**). In order to determine the impacts of subsurface drainage, the sites either had contiguous drained and undrained plots, or the measurements were made on the same plot before and after drainage was installed. A graphical representation of Robinson's results concerning the effect of subsurface drainage on peak flows based on soil texture is displayed in **Figure 2-1** (Robinson, 1990). Additionally, other field and modeling studies that have attempted to determine the impact of landscape controls are shown in **Table 2-1** and **Table 2-2.** The tables contain key landscape characteristics and the main conclusions of the studies. These studies will not be covered in much further detail but are provided as an additional resource to the reader.

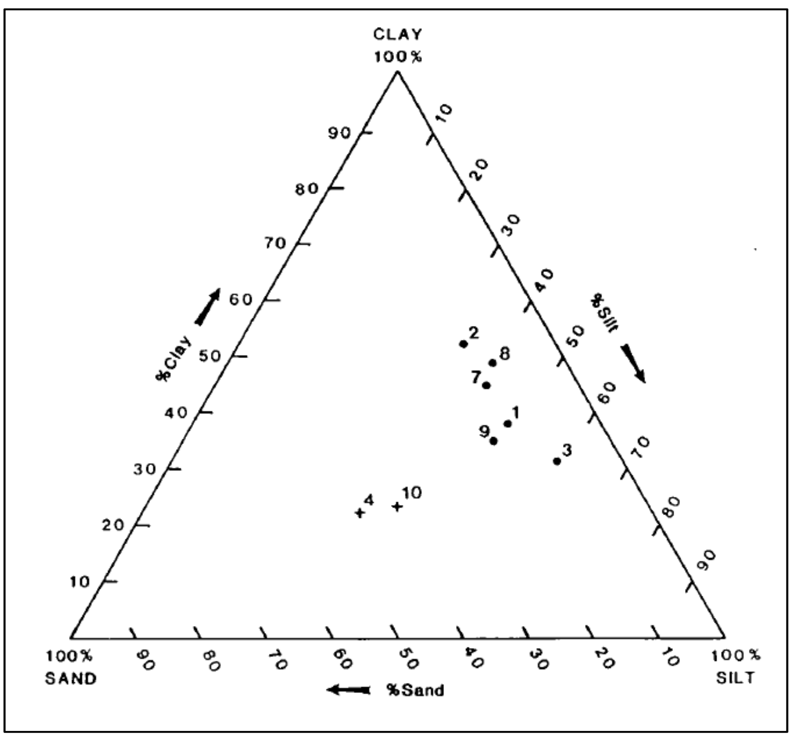


Figure 2-1 - Effects on peak flows in terms of soil texture for the eight mineral soil sites examined in Robinson's paper. The + and · symbols refer to increases and decreases in peak flows due to subsurface drainage, respectively. This figure is courtesy of Robinson (1990).

Table 2-1 - Summary of field studies to assess the hydrologic impacts of subsurface drains

Sites	Study Type	Study Type	Land Use	Area (ha)	Slope (%)	Rainfall (mm/yr)	Soil Type/Topsoil Clay Content (%)	Depth to Imperm. Layer (cm)	Effect of Drainage on Peak Flow	Control	Source
Ballinamore, Ireland	Paired	Field	Permanent Grass	0.005	17.6	1100	Clay / 38%	24	Summer Increase; Winter Decrease	Summer macropore formation in clays lead to higher peaks	Robinson 1990
Grendon Underwood, England	Paired	Field	Permanent Grass	0.25	0.5	650	Clay / 52%	24	Summer Increase; Winter Decrease	Summer macropore formation in clays lead to higher peaks	Robinson 1990
Tylwch, Wales	Bef. & Aft.	Field	Permanent Grass	1.7	2.6	1300	Silty Clay Loam / 31%	37	Decrease	High clay content	Robinson 1990
Sandusky, Ohio (US)	Paired	Field	Corn, oats, soybeans	0.55	0.30%	-	Silty Clay / 36%	-	Decrease	High clay content	McLean and Schwab, 1981
Hayes Oak, England	Paired	Field	Permanent Grass	1.8	1.5	700	Clay / 45%	25	Decrease	High clay content	Robinson 1990
Brimstone, England	Paired	Field	Cultivated w/ different practices	0.19	3.2	680	Clay / 49%	27	Decrease	High clay content	Robinson 1990
North Wyke, England	Paired	Field	Permanent Grass	1	7	1060	Clay / 35%	20	Decrease	High clay content	Robinson 1990
Cockle Park, England	Paired	Field	Cultivated	0.25	2.5	720	Clay Loam / 23%	40	Increase	Loamy Soil, Lower Clay Content	Robinson 1990
Withernwick, England	Bef. & Aft.	Field	Rotation of grass/cereals	13.5	0.3	650	Clay Loam / 22%	45	Increase	Loamy Soil, Lower Clay Content	Robinson 1990

Table 2-2 - Summary of modeling studies to assess the hydrologic impacts of subsurface drains

Sites	Study Type	Study Type	Land Use	Area (ha)	Slope (%)	Rainfall (mm/yr)	Soil Type/Topsoil Clay Content (%)	Depth to Imperm. Layer (cm)	Effect of Drainage on Peak Flow	Control	Source
Withernwick, England	-	Model	Rotation of grass/cereals	13.5	0.3	1200	Clay Loam / 22%	45	Decrease	Increase in rainfall leads to waterlogged conditions even in loamy soils	Robinson 1990
Broadhead and Skaggs, 1982	-	Model	-	-	-	~ 1250	Loam / 4.3 cm/hr	-	Decrease	High rainfall leads to more surface flow in un-drained conditions	Robinson 1990
Kohnya et al, 1988	-	Model	-	-	-	~ 1250	Mineral / 1.0 cm/hr	-	Decrease	High rainfall leads to more surface flow in un-drained conditions	Robinson 1990
Kohnya et al, 1988	-	Model	-	-	-	~ 1250	Mineral / 7.5 cm/hr	-	Decrease	High rainfall leads to more surface flow in un-drained conditions	Robinson 1990
Harms, 1986	-	Model	Grass vs. Cultivated	-	-	700	Sand / 25.0 cm/hr	-	Increase	Sandier Soil, lower rainfall	Robinson 1990
Harms, 1986	-	Model	Grass vs. Cultivated	-	-	700	Loam / 1.2 cm/hr	-	Increase	Sandier Soil, lower rainfall	Robinson 1990
Harms, 1986	-	Model	Grass vs. Cultivated	-	-	700	Clay / 0.1 cm/hr	-	No Change	Surface storage leads to more subsurface flow even in clayey soils	Robinson 1990
North Carolina		Model	Wheat-Soybean-Corn Rotation	-	-	-	Ponzer muck / 0.75 cm/hr	300	Decrease	Soil type	Kohnya, Skaggs and Gilliam 1992
North Carolina		Model	Wheat-Soybean-Corn Rotation	-	-	-	Wasda soil / 0.1 cm/hr	200	Decrease	Soil type	Kohnya, Skaggs and Gilliam 1992
Staylittle, Wales	Bef. & Aft.	Field	Permanent Grass	1.5	3.5	1800	Peat	-	Decrease	Undetermined	Robinson 1990
Blacklaw Moss, Scotland	Bef. & Aft.	Field	Rough Grazing	6.9	0.25	850	Peat	-	Increase	Undetermined	Robinson 1990

These effects found by Robinson (1990) can be explained by alterations in the flow routes when draining different types of soils. The low permeability of clayey soils leads to frequent waterlogging, and therefore significant surface runoff. Installation of tile drainage in these soils increases the effective permeability of the soil, and thus increases the proportion of the total flow that is routed through the subsurface pathway. Subsurface pathways attenuate the flow to a greater extent than surface pathways, which leads to the observed decrease in peak flow with the installation of drainage in clayey soils. On the contrary, in sandy soils, the permeability of the subsurface is high, and the flow is therefore routed primarily through the subsurface under undrained conditions. The installation of artificial drainage systems in these soils increases the permeability of the subsurface, which leads to an increase in peak flow.

Soil type, however, is not the only factor that affects peak flow response to subsurface drainage. The existence of macropores and/or surface storage (depressions in the landscape) has been shown to counter the effect of soil type (Robinson, 1990; Schwab, Fausey, Desmond, & Holman, 1985). At two of the clay sites in the UK study (Ballinamore and Grendon), peak flows were observed to increase due to the installation of drainage in the dry summer months, while it exhibited the more expected decrease during the other seasons (**Figure 2-2**). This seasonality in peak flow was attributed to the creation in the dry summer months of macropores that resulted from the clay soils cracking. Schwab et al. (1985) also found similar results with increases in peak flows during certain storm events due to the formation of macropores caused by cracking in the Toledo clay soil (Robinson & Rycroft, 1999).

Flow routes can also be used to explain the role of macropores in altering the effect of drainage on peak flows. Clayey soils are susceptible to macropore formation, which consists of shrinkage cracks, root channels, biopores, and any other structural disturbances. The presence of macropores causes the flow to be routed rapidly through the subsurface pathway, similar to the flow in a sandy soil, even when the soil is predominantly composed of clay. Tile drains can encourage further macropore formation by drying the soil, which causes cracking due to shrinkage and creates more defined subsurface flow paths (Robinson & Rycroft, 1999). Installation of drainage in such soils thus creates an effective and fast bypass flow pathway through the macropore-tile network, which leads to an increase in the peak flow instead of the more expected decrease. An increase in surface storage has a similar effect. Depressional stores in the landscape reduce surface runoff and increase infiltration, which means that flow through the subsurface pathway is greater than in a similar soil type without surface stores. Consequently, the installation of drainage in such scenarios might not lead to the expected decrease in peak flow with drainage in clayey soils.

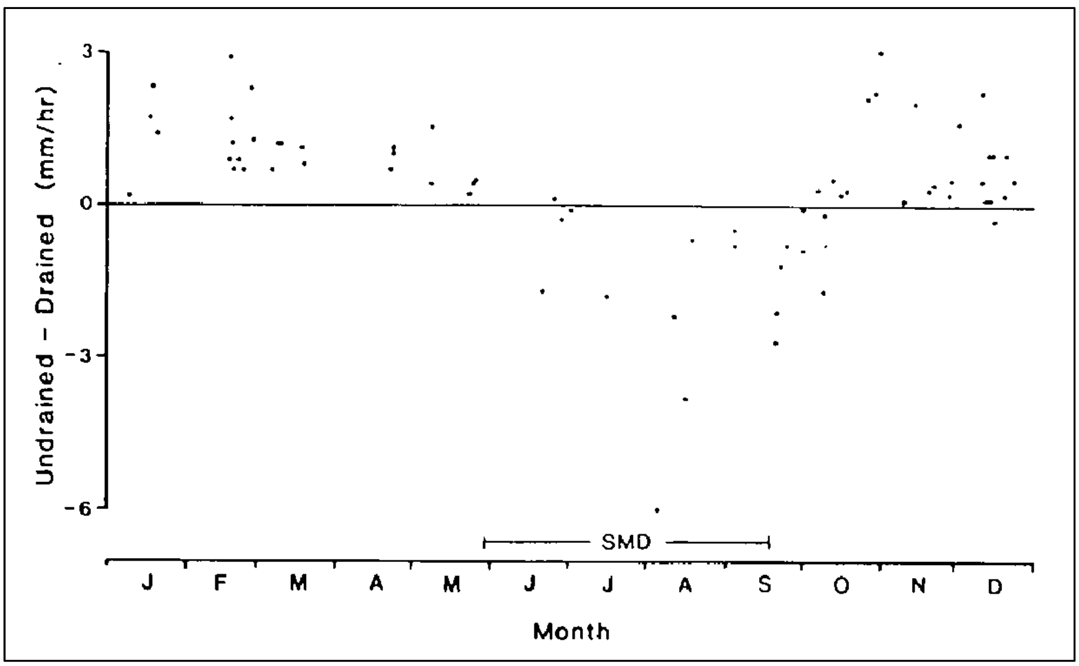


Figure 2-2 - Differences in storm hydrograph peaks between the drained and undrained site during a year at Ballinamore, courtesy of Robinson, 1990.

The opposite effects that tile drains have on clayey (decreasing peakflows) versus sandy soils (increasing peakflows) indicates that tiles reduce the spatial heterogeneity of hydrologic response at the watershed scale, arising from different soil types in the watershed. This is illustrated in **Figure 2-3,** in which the unit hydrograph peaks and time to peak of different soil types are observed to change in different directions from tiling, thereby removing some of the effects of the soil type.

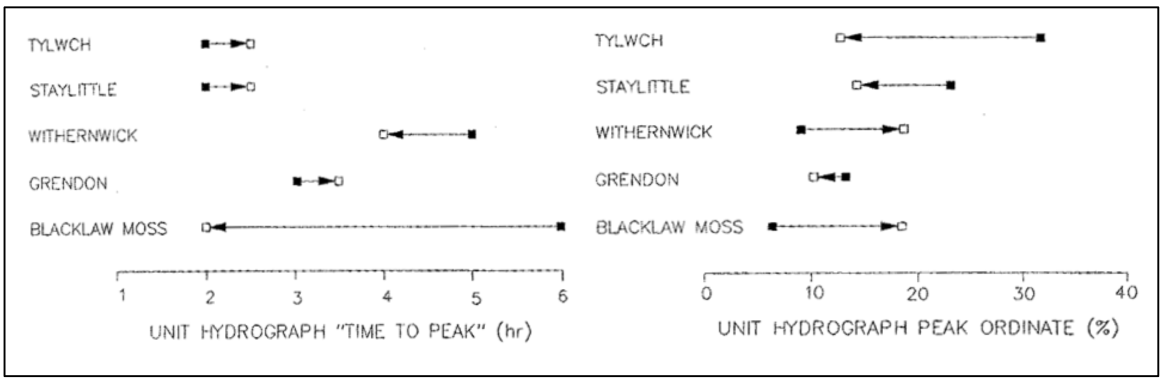


Figure 2-3 - The effects of subsurface drainage on peaks and times to peak. The white and black blocks represent post- and pre-drainage results, respectively. Figure courtesy of Robinson and Rycroft (1999).

2.3 Climatic Controls: Precipitation and Evapotranspiration

Precipitation is the other dominant control in determining the effect of the installation of subsurface drainage on peak flows. The impact of precipitation characteristics on tiles is difficult to determine due to the complexity of rainfall patterns and the limited number of studies. Field studies in clayey soils indicate that, while installation consistently decreases peak flow, the greatest reductions in peak occurred during the most intense storms (McLean and Schwab, 1982). Drainage reduced by 32% the peak flows from storm intensities greater than 3 inches/day, while peak flows from storm events greater than 5.9 inches/day were reduced by 46% (Schwab, Fausey, Desmond, & Holman, 1985; Robinson & Rycroft, 1999).

Vidon and Cuadra (2011) studied the effects of precipitation characteristics and the antecedent moisture condition (AMC) on tile drain flows. The experiment was performed on two constantly monitored tile drains in the Leary Weber Ditch Watershed near Indianapolis, IN. The site was mainly composed of Crosby-Brookston silty loams and required tiles to remove ponding and lower the water table for the planting of soybeans. Eight storm events that produced tile flows were analyzed from April to June of 2008. A correlation analysis was performed between the antecedent water table depth, multiple precipitation characteristics, and multiple tile flow characteristics. The total precipitation was found to be highly positively correlated (99% significance level) to mean tile flow, maximum tile flow, time to peak, and runoff ratio. The antecedent water table depth was positively correlated (95% significance level) to the mean tile flow, max tile flow, hydrograph response time, and runoff ratio. The maximum precipitation intensity was negatively correlated (99% significance level) to the hydrograph response time, indicating the effect of increased macropore flow with increasing rainfall intensity. However, these results were only for one soybean field in spring. Vidon and Cuadra (2011) showed that a similar storm in the summer produced significantly less tile flow due to crop water demand, indicating the role of evapotranspiration and land-use in moderating tile flows.

In addition to field data, model simulations have been used to explore the effect of precipitation on peak flow. At the Withernwick field site in the UK, a DRAINMOD (discussed in Section 3.2) analysis found that subsurface drainage increased the peak flow, and the increase was attributed to the higher permeability of the site (Robinson et al., 1990). However, when a DRAINMOD analysis was performed at the same site using twice the rainfall input (1200 mm/yr in contrast to the field site rainfall of 650 mm/yr), drainage was observed to actually decrease the peak flow, which was the opposite of the field plot results. The increased precipitation caused a large amount of surface runoff in the undrained scenario, which increased peak flows. Tile drainage allowed for the bypassing of potential surface runoff through the subsurface, which led to the observed decrease. Broadhead and Skaggs (1982) modeled a loamy soil with annual rainfall equal to 1250 mm and found that drainage decreased peak flows, which supports Robinson's model results at Withernwick. Consistent with these two studies, Kohnya modeled two mineral soils (K = 7.5 cm/hr vs. K = 1.0 cm/hr), with an annual rainfall ~ 1250 mm, and observed reductions in peak flows due to the installation of subsurface drainage. Harms (1986) tested a sandy, loamy, and clayey soil with an annual precipitation equal to 700 mm. Drainage was noted to increase peak flows in the sandy and loamy soil, while no change was observed in the clayey soil. The results for the more permeable sand and loam were expected, but the clay result was not. Robinson (1990) attributed the discrepency to Harms halving the surface storage of the drained soil as compared to undrained. This change caused more frequent surface runoff and higher peaks but highlights the importance of the surface storage parameter.

The field and modeling results point to the importance of pre-drainage water conditions in determining the impact of drainage on peak flows. Subsurface drainage decreases the peak flow for clayey soils that are normally waterlogged before drainage due to low permeability of clayey soils, while it increases peak flow in sandy/loamy soils that are normally drier. However, with higher mean annual precipitation, a sandy/loamy soil might be more frequently waterlogged, leading to a decrease in peak flow with drainage.

2.4 Anthropogenic Controls: Drainage Design

Finally, the spacing of tile drains and the depth at which they are placed also play a role in modifying the hydrologic response. Studies exploring this effect have predominantly relied on the use of models (Robinson, 1990). In one DRAINMOD study for Webster and Canisteo soils in Iowa (Singh and Helmers, 2006), the optimal drain spacing that reduces the amount of subsurface drainage without causing excess water stress to crops was found to be equal to 25 m for a drainage intensity of 0.46 cm/day and a drain depth of 1.05 m. DRAINMOD simulations also revealed that for poorly drained sites, decreasing drainage spacing initially decreases the peak flows as more flow is routed through the subsurface. However, beyond an optimal point, as the drain spacing decreases even further, there is a point at which the peak flows from the site will increase because the hydraulic gradient to the tiles is steep and the subsurface flow becomes fast (Robinson, 1990). This observed saddle-shape behavior was used by Wiskow and van der Ploeg (2003) to develop a semi-analytical procedure in order to determine an optimal drain-spacing that would allow for highest soil water retention during extreme rainfall events, thereby attenuating daily peak flows.

In addition to the drain spacing, the capacity of a drainage system can also impact peak flows during large or consecutive storm events. During large events, the subsurface storage may be filled and surface runoff will dominate. During multiple events, the antecedent moisture conditions of lower capacity drainage systems can cause the storage to fill as well, allowing for more surface runoff than higher capacity systems and, therefore, higher peak flows (Skaggs, Breve, & Gilliam, 1994).

Management practices such as surface mulching were observed to reduce peak flows, especially on plowed, bare soil (Robinson & Rycroft, 1999). The reduction is due to a decrease in the kinetic energy of rain drops hitting the surface, which will reduce surface sealing and increase infiltration. Additionally, other studies have shown that under an established crop, plowed clay soils can reduce peak flow as compared to minimal tillage. This is due to an increased permeability of the clay soil from tillage, which will allow for greater infiltration. Also, the tillage breaks up the continuous flow paths of macropores, thereby reducing seasonally high peak discharges in the tiles (Robinson & Rycroft, 1999).

2.5 Synthesis and Knowledge Gaps

The effect of the different landscape, climatological, and anthropogenic factors on how subsurface drainage modifies hydrologic response is captured in **Figure 2-4**. The indicator used in the **Figure 2-4** is the Richard-Baker Flashiness Index and is explained in Section 3.3.4. Several key conclusions can be drawn from the literature review:

1. The flow pathway of water prior to the installation of the subsurface drainage is the key factor that controls the role of subsurface drainage in altering the peak flow.
2. For waterlogged soils with predominantly surface flow pathways, subsurface drainage leads to a greater fraction of the flow being routed through the slower subsurface pathway, which yields a decrease in peak flow. By contrast, in drier soils where the subsurface flow pathway dominates, the introduction of subsurface drainage can increase peak flows due to the faster routing of the water.
3. Whether or not a landscape element is waterlogged is a function of a suite of factors including soil type, presence of macropores and surface storage, depth to impermeable layer, rainfall, crop water demand, spacing of the subsurface drains, and spatial location. All of these factors contribute to answering the complex question of the role of subsurface drainage on altering the hydrologic response.
4. Clay soils are mostly waterlogged and dominated by surface flows, while sandy soils are mostly drier and dominated by subsurface flows. Consequently, most studies have found that subsurface drains decrease peak flows in clayey soils and increase peak flows in sandy soils. However, if clay soils have macropores, or surface storage, the subsurface flow routes are more dominant, which leads to an increase in peak flow with drainage. Conversely, if a sandy soil exists in a high rainfall area, it might be waterlogged for most of the time, which yields a decrease in peak flow with drainage.

5. Indeed, precipitation is a key driver of the impacts of subsurface drainage. Though there are fewer studies that focus on the impacts of precipitation on drainage, there are some key qualitative conclusions. The intensity of rainfall has also been shown to increase the amount of peak reduction created by subsurface drainage. However, if the intensity exceeds the infiltration capacity of a soil, the impacts of drainage are null. The frequency of storms also has an impact. Consecutive storm events can have an impact on flood peaks, depending on how much storage is available in the subsurface and how the surface runoff peaks interact with the peaks from the subsurface drains.
6. While the effect of subsurface drainage on peak flows is mired in complexity, all studies reported that the total volume of runoff was unimpacted by drainage, while the baseflow increases after drainage.

In summary, to answer how subsurface drainage impacts hydrology, it is critical to consider the complex interplay of landscape (soil type, macropores, surface storage), climatic (rainfall, evapo-transpiration), and anthropogenic (drainage spacing, drainage capacity, etc.) factors. As mentioned previously, these conclusions are only applicable at the field scale. Therefore, in order to get a holistic view of the tile drainage impacts on hydrology, a comprehensive simulation study was performed at both the field scale, utilizing the three main controls, and at the catchment scale.

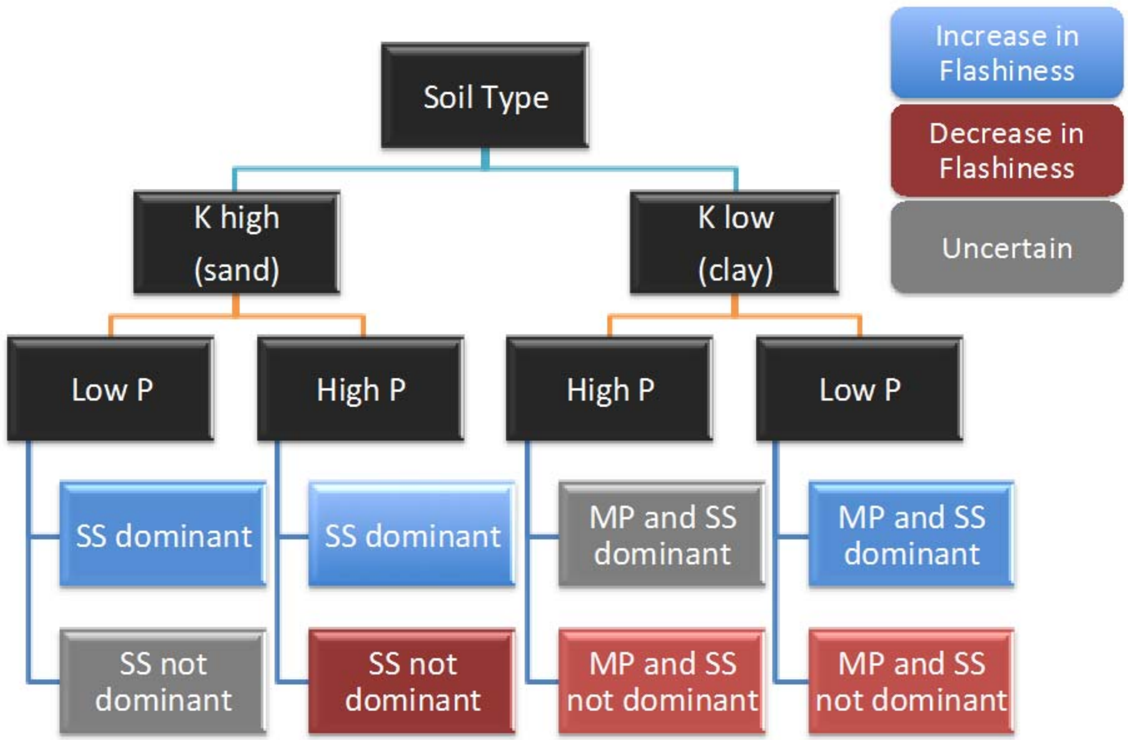


Figure 2-4 - Synthesis of climate and landscape controls on hydrologic response to tile drainage. In the figure, P = precipitation, SS = surface storage, and MP = macropores. Blue indicates an increase in flashiness, while red indicates a decrease in flashiness. While flashiness mostly decreases in clayey soils following drainage installation (as indicated by more reds), it might increase under certain rainfall and soil factors. The opposite is true for sandy soils.

CHAPTER 3: THE IMPACTS OF TILE DRAINAGE ON HYDROLOGIC RESPONSE AT THE FIELD SCALE

3.1 Rationale for Field Scale Analysis

The objective of this section is to determine the hydrologic impacts of tile drainage at the field scale in terms of landscape, climatic, and anthropogenic controls, which are conceptualized in **Figure 3-1**. The deterministic field scale model, DRAINMOD, is used to analyze this three-pronged approach for extreme scenarios and scenarios that are typical to Iowa. Sections 3.2 and 3.3 contain descriptions of DRAINMOD and the methodology of collecting and inputting data for the DRAINMOD simulations. Section 3.4 contains the results of the analysis of the three controls. The landscape controls section (Section 3.4.2) uses 6 different soil types as well as 7 different surface storage depths to determine how field characteristics affect tile impacts. The climate controls section (Section 3.4.3) uses 30 years of hourly rainfall data from Iowa City, IA to determine how rainfall characteristics influence the impact of tiling. The anthropogenic controls section (Section 3.4.4) uses a variation on tile spacing to determine the effects of installation on the hydrologic response.

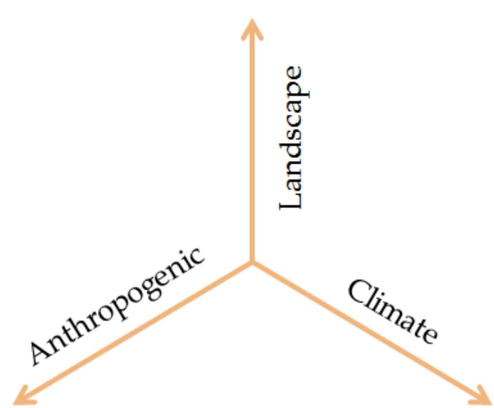


Figure 3-1 - The three controls that dictate the hydrologic response of agricultural tile drainage at the field scale.

3.2 DRAINMOD Description

DRAINMOD Version 6.1 is the model selected for this study on the hydrologic impacts of tile drainage. DRAINMOD is a field scale, process based, distributed simulation model that was developed by the Biological and Agricultural Engineering Department at North Carolina State University under the direction of Dr. Wayne Skaggs. It has been used extensively over the past 30 years to model the hydrology in poorly-drained, tiled soils in the United States. DRAINMOD calculates the surface and subsurface water balance for a thin column of soil that has a unit surface area that extends from the surface to a subsurface impermeable layer and that is located at the midway point between two tile drains. The water balance is calculated primarily at an hourly time increment, using approximate methods based on weather, soil, and drainage design inputs (Skaggs R. W., 1981). The two governing water balance equations for the surface and subsurface are:

$$P = F + \Delta S + RO \tag{3.1}$$

$$\Delta V_a = D + ET + DLS - F \tag{3.2}$$

where P is precipitation, F is infiltration, ΔS is change in surface storage, RO is surface runoff, ΔV_a is the change in the volume of air voids in the subsurface, D is tile drainage, ET is evapotranspiration, and DLS is deep and lateral seepage. All of the components' area-normalized units are measured in centimeters (cm) because the soil column has a unit surface area, and the link between the surface and subsurface equations is the infiltration (F) term. Each of these components is calculated using approximate methods which allow DRAINMOD to run long-term simulations very quickly. **Figure 3-2** illustrates the key hydrologic components represented by DRAINMOD.

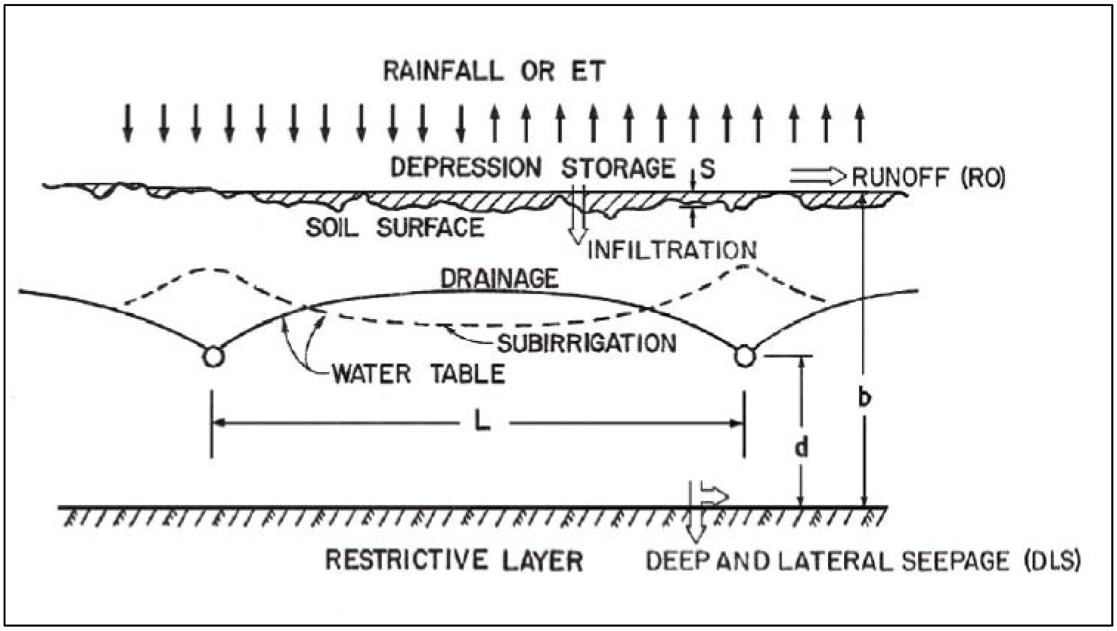


Figure 3-2 - Hydrologic processes represented by the DRAINMOD, courtesy of Skaggs (2012).

A brief overview of the key methods and equations behind the water balance components in DRAINMOD is crucial to understanding the strengths and weaknesses of this modeling approach. The most important inputs into DRAINMOD are definitely the soil parameters. These parameters are used to create the following four key tables that dictate the behavior of the approximate water balance equations:

1. **Soil water characteristic curve, θ(h):** This curve is a measure of water retention (volumetric water content (cm^3/cm^3) vs. head (cm)) in the unsaturated zone and can be created either using laboratory tension tables or the Van Genuchten water retention function, given the appropriate unsaturated soil inputs.
2. **Drainage Volume (cm) vs. Water Table Depth (cm):** This table is calculated from θ(h) and determines the new water table depth based on inflows and outflows to and from the subsurface.

3. **Upward Flux (cm/hr) vs. Water Table Depth (cm):** This table is a measure of capillary rise and dictates the amount of water available to the root zone for ET. The upward flux curve can be created mathematically from the unsaturated hydraulic conductivity ($K_{us}(h)$) function, but given the sparseness of that data, the saturated vertical hydraulic conductivity (K_V) and θ(h) are used to approximate $K_{us}(h)$ using the Millington and Quirk method.
4. **Green-Ampt Parameters vs. Water Table Depth (cm):** This table is calculated from θ(h) and K_V and determines the infiltration rate curve based on the water table depth at a given time step.

These four tables are interpolated to obtain values that serve as inputs, links, or thresholds to the governing approximate equations for each hydrologic process represented in DRAINMOD. The two key parameters are K_V and θ(h) because they are used in calculating the other tables and in some of the hydrologic equations. It is also important to note that these tables are created under the assumption that the soil water distribution in the unsaturated zone is drained to equilibrium (hydrostatic). It was found through laboratory tests that the unsaturated zone essentially keeps pace with the water table because water leaves the subsurface very slowly (Skaggs R. W., 1981).

Infiltration is calculated using **Equation 3.3, t**he Green-Ampt equation:

$$f = K_V + K_V M_d S_f / F \tag{3.3}$$

where f is infiltration (cm), K_V is vertical hydraulic conductivity (cm/hr), M_d is the difference between the final and initial volumetric water content (cm^3/cm^3), S_f is the effective suction at the wetting front (cm), and F is cumulative infiltration. However, this original equation assumes complete saturation behind the wetting front, which may be unrealistic; therefore, a relaxed version of the Green-Ampt equation developed by Philip in 1954 is used (**Equation 3.4**):

$$f = B + A/F \tag{3.4}$$

where A and B are parameters developed for each soil type, based on the initial water content and soil water distribution. Additionally, at times where rainfall is below infiltration capacity, DRAINMOD assumes that the infiltration rate is equal to the rainfall rate. The parameters A and B are used to fit different infiltration curves based on the initial water table depth at the start of a time period. These parameters are the fourth key table mentioned above, and an example of the multiple infiltration curves at different water table depths is shown below in **Figure 3-3**.

The other three parameters of **Equation 3.1** are more simplistic than infiltration. Precipitation can be either an hourly or a daily input, which DRAINMOD will split up equally according to a user-specified time interval. Surface storage is simply defined as a depth (cm) since DRAINMOD is area-normalized, and once the surface storage is filled, water is immediately accounted for as surface runoff. This neglects any routing or spatial heterogeneity of surface storage, making the storage depth an important parameter. This assumption of immediate runoff and constant surface storage has proven sufficient for the numerous studies performed with DRAINMOD.

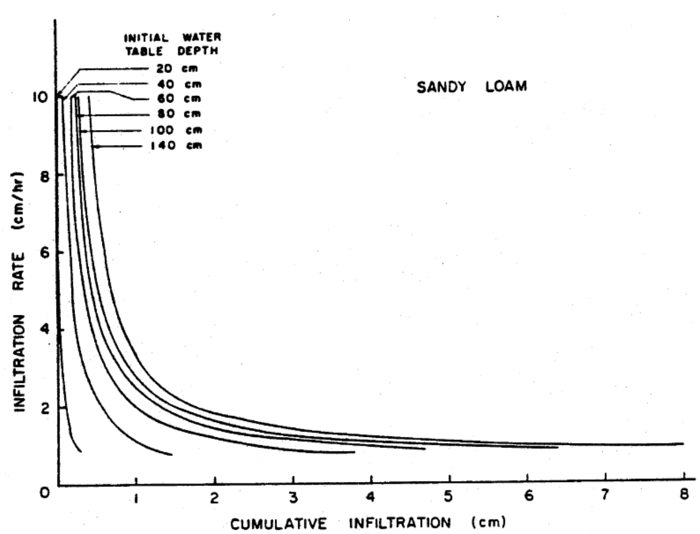


Figure 3-3 - Infiltration curves used in DRAINMOD based on Green Ampt Parameters A and B for different water table depths (Skaggs R. W., 1981).

Once water has infiltrated into the subsurface, it can exit through tile drainage, ET, or seepage. Obviously, for this study, the equation used to describe tile drainage is very important. There are three ways that tile drainage can be represented based on water table levels and drainage design: the steady-state Houghoudt equation, Kirkham's equation, or the drainage coefficient. The steady-state Houghoudt equation (**Equation 3.5**) is applied when the water table is between the drain depth and the surface level. The equation includes Dupuit-Forcheimer (D-F) assumptions (lateral flow in the saturated zone only) and an elliptical water table.

$$q = \frac{4K_e m(2d_e + m)}{L^2} \tag{3.5}$$

where q is the tile discharge per unit area (cm/hr), K_e is the effective lateral saturated hydraulic conductivity (cm/hr), m is the midpoint water table elevation, L is the drain spacing (cm), and d_e is the equivalent depth from the impermeable layer, which is defined by two more equations based on the ratio of actual depth to impermeable layer, entrance losses to tile drains (effective radius, r_e), and drain spacing. The equivalent depth is used instead of the actual depth in order to correct for convergence near the drains. The reader is referred to the DRAINMOD manual for the equations and theory behind equivalent depth. Once the water table reaches the surface and ponds to a point where it can move freely to the area above the drains, DRAINMOD switches to Kirkham's equation, (**Equation 3.6**):

$$q = \frac{4K_e \pi(\mathrm{t+b-r})}{\mathrm{gL}} \tag{3.6}$$

where t is the ponded surface water depth (cm), b is the depth of the center of the tile drain from the surface (cm), r is the drain tube radius, and g is a constant calculated from the drain radius, spacing, and depth to impermeable layer. Once again, the reader is referred to the DRAINMOD manual for more information on g. Kirkham's equation is used since the D-F assumptions no longer hold because most of the water will be infiltrating and entering the tiles in the immediate area surrounding the drains. Finally, tile flow is also dictated by the capacity of the system, which is defined by the user as the drainage coefficient (cm/day) in DRAINMOD. Drainage coefficients based on pipe size, slope, and orientation can be obtained from practical sources like the Iowa Drainage Guide. **Figure 3-4** is used to help illustrate the water table conditions at which the two tile drainage equations are applied. Given that the drainage coefficient is large enough, Houghoudt's equation is used when $c < m < s_2$, and Kirkham's equation is used when $s_2 < m < s_1$. Another important note is that the water table height, m, is located at the midway point between drains and not across the entire field since an elliptical water table is assumed. The vertical scale in **Figure 3-4** is exaggerated, and this midway water table height can typically be assumed with limited error across the field (Skaggs, Youssef, & G.M. Chescheir, 2012).

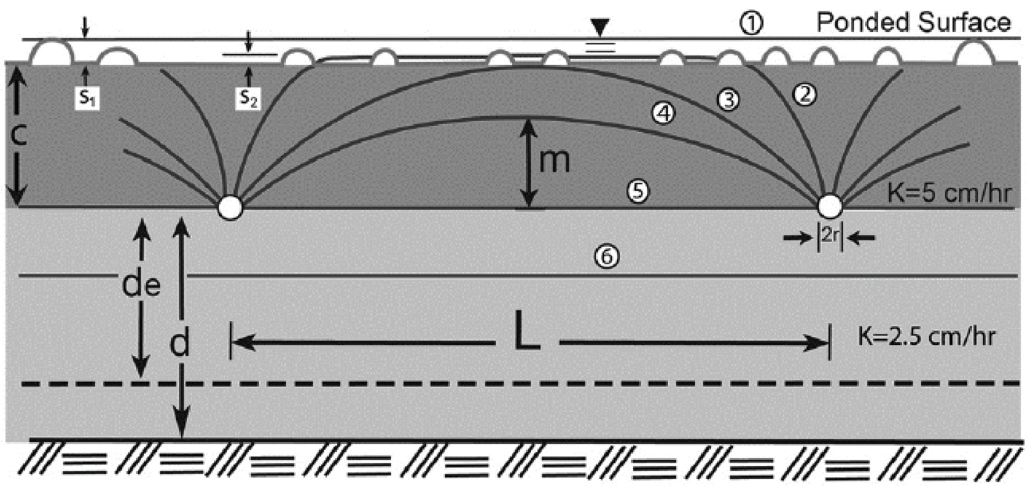


Figure 3-4 - Theoretical diagram of tile flow using Houghoudt's and Kirkham's equations, courtesy of Skaggs, Youssef, and G.M. Cheschair (2012).

Deep and lateral seepage are another subsurface flow pathway simulated by DRAINMOD. Lateral and deep seepage are both derived from Darcy's law and are as follows:

$$q_L = \frac{K_L(h_1{}^2 - h_2{}^2)}{2x} \tag{3.7}$$

$$q_V = \frac{K_V(h_1 + d_V - h_V)}{d_V} \tag{3.8}$$

where q_L is the lateral seepage per unit area (cm/d), K_L is the lateral hydraulic conductivity of the soil layer (cm/d), h_1 is the water table elevation above the impermeable layer, h_2 is the hydraulic head of the receiving waters (ditch, another field's water table, or aquifer), x is the distance to the receiving waters from the midway point of the drains, q_V is the vertical seepage per unit area (cm/d), K_V is the vertical hydraulic conductivity of the restrictive layer (cm/d), d_V is the restrictive layer thickness (cm), and h_V is the hydraulic head of the deep aquifer, measured from the bottom of the restrictive layer (cm) (Skaggs, Youssef, & G.M. Chescheir, 2012). Lateral seepage is very important to this study, especially when modeling undrained fields, since it is the primary subsurface output. There was also a recent development in the model of lateral seepage for a sloped water table, which now allows users to apply DRAINMOD to a wider range of fields with greater slopes, but it was not used in this analysis. The fields analyzed in this study are assumed for simplicity to be poorly drained agricultural field that have little regional groundwater movement and drain to a channel or ditch only. Therefore, a constant head boundary representing flow to a channel from the perched water table was set for the simulations and will be discussed later in the model inputs section.

Evapotranspiration is the final subsurface process used in this study that is modeled by DRAINMOD. ET is estimated using the Thornthwaite method, which, according to the manual, is inaccurate but has proven effective for the uses of DRAINMOD (Skaggs R. W., 1981). The equation for the Thornthwaite method is:

$$e_j = c\bar{T}_j{}^a \tag{3.9}$$

where e_j is the monthly potential evapotranspiration (PET), $\bar{T}_j$ is the monthly mean temperature (°C), and a and c are constants calculated from the annual heat index, I:

$$I = \sum_{j=1}^{12} \left(\frac{\bar{T}_j}{5}\right)^{1.514} \tag{3.10}$$

The monthly PET values are then converted to daily values using the methods described by Thornthwaite and Mather (1957). Since this method is strictly empirical and uncertain, there is a multiplier that can be applied to monthly PET values for calibration purposes. There is also the option in DRAINMOD to input daily or monthly ET values that were calculated or obtained outside of the model, but the Thornthwaite method was sufficient for this study.

The calculated PET value is the actual ET only if there is sufficient water supplied from the subsurface. The amount of water available for ET is based on crop characteristics and the upward flux vs. water table curve described above. The subsurface is divided into two layers, a wet zone, which extends from the water table to the bottom of the root zone (and possibly through it), and the dry zone, which is determined by the effective root depth during the particular time of the year. The effective root depth accounts for the fact that the majority of water is collected closer to the surface instead of by the longest roots and is typically 50-60% of the actual root length. The PET can be fulfilled by the upward flux (capillary rise) if the water table is high enough and/or water is stored in the dry zone. The dry zone is the first zone filled with infiltrated water before the wet zone is recharged, and it mimics how plant roots hold water. If there is not enough water available for ET from the upward flux (capillary rise), then the dry zone provides water until it either meets the PET demand or reaches a user-defined critical water content (typically the wilting point). If there is not enough water supplied by both mechanisms, then the actual ET will be less than the PET. The dry zone will change depths during the growing season based on the effective root depths input into the model. This change in the dry zone also impacts the upward flux since the table defining this process is based on the water table depth below the root zone. Additionally, stress factors and relative yield are calculated based on the soil water conditions over the year, since that is one of the primary reasons for the creation of DRAINMOD: to model how tiles assist crop production. However, the stresses do not impact the root depth, and the only way to affect root depth is to delay the planting date, which could be a possible source of error. However, given the approximate nature of ET estimation, the crop inputs are typically used as calibration parameters and perform sufficiently (Skaggs R. W., 1981).

DRAINMOD has also added a freeze-thaw algorithm in the past decade to mimic snow accumulation, snow-melt, and subsurface flow processes that are affected by frost. This algorithm was utilized in the study but was not extremely important given that larger summer events were of more interest than snowmelt events. DRAINMOD has many other features not used in this study, including management practices (controlled drainage) and nitrogen transport (DRAINMOD-N). Only the basic hydrologic capabilities were used for this study.

3.3 Methodology

3.3.1 Pre-Calibrated Model for Webster Soil

DRAINMOD has been utilized in many studies over the past 30 years, ranging from hydrologic impacts to nutrient loading. Recently, Singh and Helmers (2006) calibrated and validated a DRAINMOD model for two common Iowa soils: Webster and Canisteo. The calibrated Webster model was the baseline for this field scale analysis. The actual soils are not used in this study, in favor of more general USDA soil textural classes, but the crop input, surface storage, PET adjustment parameters, drainage design inputs, and soil freeze-thaw parameters were all used in the simulations for this analysis. Dr. Matt Helmers from Iowa State University (ISU) provided the input files for the calibrated Webster soil model, which greatly helped this research.

The models were calibrated on ISU's experimental plots near Gilmore City, Iowa for both of the clay loam soils. Tile flow was collected from five 0.05 hectare (ha) field plots of each soil type, with 7.6 m tile spacing and a depth of 1.06 m. The Webster soil had a continuous corn rotation, while the Canisteo soil had a corn-soybean rotation. The model was calibrated using data from 1990-1993 and was validated with data from 1994-2003. The study used the Iowa Soil Properties and Interpretations Database (ISPAID) Version 7.0 and the pedotransfer function ROSETTA to predict the soil hydraulic parameters that were necessary as inputs to DRAINMOD. The non-linear parameter estimation program, PEST, was used to calibrate the tile flow volumes from 2-3 week periods of data collection using K_L, K_V, and a shape parameter (α) as the calibration parameters (Singh, Helmers, & Qi, 2006). The results of the validation period were reasonable for the two soils, and the predicted and observed values for the Webster soil calibration and validation period are shown below in **Figure 3-5**. These model results, besides giving baseline inputs for this field scale study, show how DRAINMOD can be easily utilized using widely available data and a pedotransfer function. The study goes on to determine the optimal spacing to reduce tile flow in the interest of reducing nutrient loading while maximizing relative yield, but that is outside of the scope of this chapter.

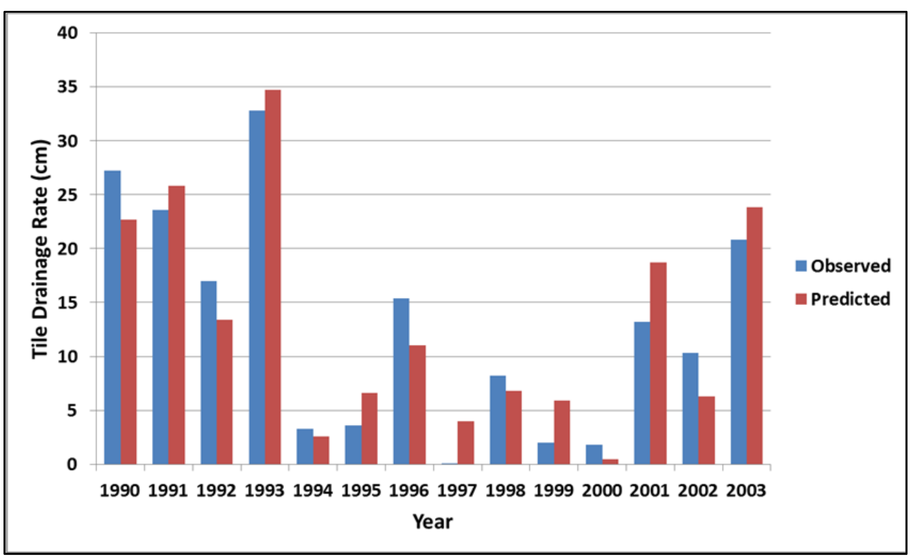


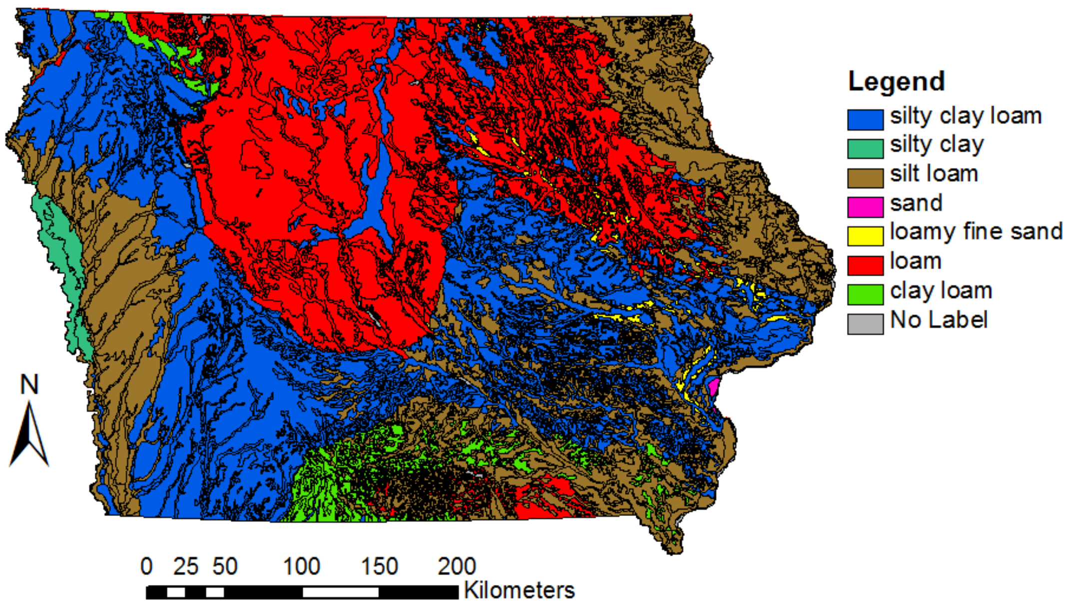
Figure 3-5 - DRAINMOD prediction results for Webster soil experimental plots near Gilmore City, courtesy of Singh and Helmers (2006).

3.3.2 DRAINMOD Inputs for Field Scale Analysis

The study by Singh and Helmers (2006) analyzed two soil types using extensive field scale data. However, the purpose of this study is to analyze the impacts in terms of a range of soil types, climate inputs, and drainage designs that are typical to Iowa. Therefore, given the difficulty of obtaining tile flow data from different soil types across Iowa, a large assumption needed to be made: the pre-calibrated Webster soil model is realistic enough so that changing soil types, weather inputs, and drainage spacing, significant patterns and fundamental answers to tiling's impact on hydrology can be obtained. The first step was to ascertain the appropriate types of soil to analyze that are relevant to Iowa. The USDA-NRCS United States General Soil map (STATSGO2) was used to determine the main soil types according to the USDA textural classification system because the class-averaged soil hydraulic properties are readily available for these soil types and the results obtained from these general soil types should still be applicable to typical Iowa soils. **Figure 3-6** shows the general soil textures across Iowa. Additionally, **Figure 3-6** includes a map from the Iowa DNR that predicts the soils that would require tile drainage to achieve optimal agronomic yields from row crops. The second map was created by using two methods that determine the need for drainage by assessing an area's soil drainage class and average slope.

The two maps helped determine which soils were selected for this field scale analysis. The soil texture map indicates that much of Iowa is classified as silt clay loam, silt loam, and loam. The map is a very general representation of the soil types contained in the areas, but many of these soil types are poorly drained. This is corroborated by the second plot of soils that may require tiling. Clearly, many of the poorly-drained loamy soils in the Des Moines Lobe (north central portion of Iowa) would require drainage. This is very well known considering the large amounts of prairie potholes located in the Des Moines Lobe that have been drained for agriculture over the past century. The southern portion of Iowa also has soils that would possibly need drainage. Therefore,

A) General Iowa Soil Map



B) Soils Requiring Drainage

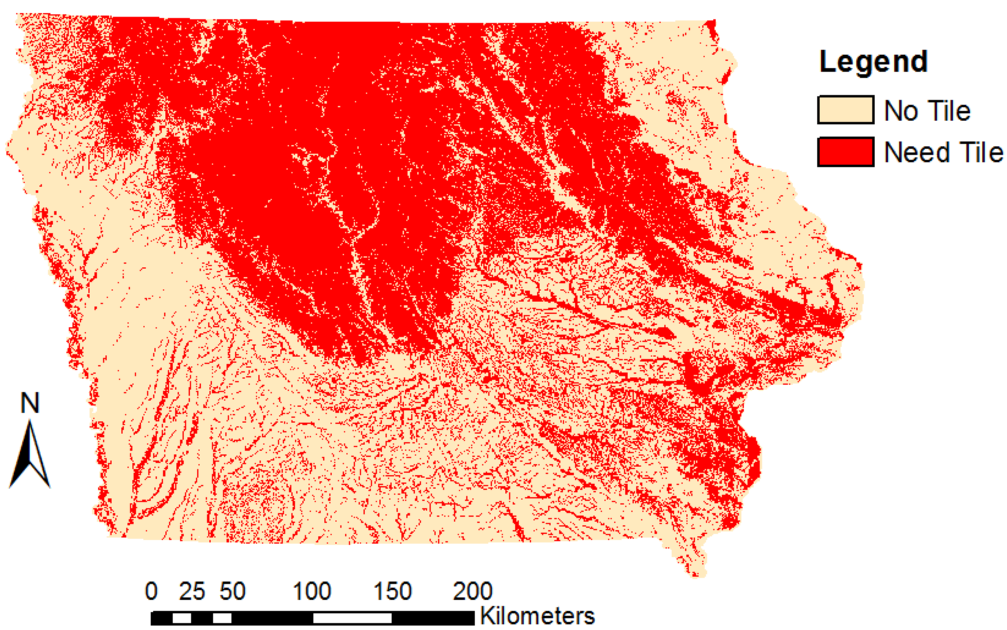


Figure 3-6 - Maps describing the main soil textural classes and drainage requirements for the state of Iowa according USDA-NRCS and the Iowa DNR.

three of the soils selected for analysis are loam, silt loam, and silty clay loam, because they are prevalent in Iowa and possibly require drainage. Additionally, it is important to get an idea of the end member soil types, so sand, silt, and clay are also analyzed in this study.

The hydraulic parameters for these soil textural classes to be input into DRAINMOD are readily available from the USDA. The hydraulic parameters for the 12 USDA textural classes are shown below in **Table 3-1**. The class average values of saturated water content, θ_s (cm^3/cm^3), residual water content, θ_s (cm^3/cm^3), curve shape parameters α (1/cm) and n (-), and K_{sat} (cm/day) are calculated for each class and are then inserted into the Van Genuchten model via ROSETTA to obtain values for the tortuosity parameter, L (-), and matching point at saturation, K_o (cm/day). These hydraulic parameters are input into the soil utility function in DRAINMOD to create the four key tables described in Section 3.1, which are then stored in the .SIN and .MIS files. The saturated lateral hydraulic conductivity (K_L) was assumed to be 1.4 times K_V, and the depth to impermeable layer was assumed be 3.9 m. These two assumptions are very important because they help define tile flow as well as seepage, but they are variable parameters that are not widely available. Therefore, for simplicity, they, as well as the soil temperature characteristics, were both assumed to be the same as Singh and Helmers (2006). This assumption could incur error, but considering the fact that the assumptions are also based on field work, it was the most realistic option available for this analysis. The next most important input for DRAINMOD is the weather data. Hourly precipitation data were obtained from the NOAA National Climatic Data Center for Iowa City, Iowa (COOP #134101) for the years ranging from 1981 to 2010. These data were selected based on the quality and length of the dataset and because it seemed like a variable collection of rainfall years with values ranging from 295 mm to 1504 mm of annual precipitation. The hourly data were formatted and inserted into DRAINMOD's weather utility program to create the .RAI input file. Daily minimum and maximum temperature data were also collected from the NCDC and input into the weather utility program to create the .TEM input file. The PET adjustment factors were left the same as Singh and Helmers (2006).

Table 3-1 - Class average soil hydraulic functions using ROSETTA, courtesy of the USDA-NRCS (USDA - Agricultural Research Services, 2005).

Texture Class	N	-- θr -- cm3/cm3		-- θs -- cm3/cm3		-- log(α) -- log(1/cm)		-- log(n) -- log10		-- Ks -- log(cm/day)		-- Ko -- log(cm/day)		-- L --	
Clay	84	0.098	(0.107)	0.459	(0.079)	-1.825	(0.68)	0.098	(0.07)	1.169	(0.92)	0.472	(0.26)	-1.561	(1.39)
C loam	140	0.079	(0.076)	0.442	(0.079)	-1.801	(0.69)	0.151	(0.12)	0.913	(1.09)	0.699	(0.23)	-0.763	(0.90)
Loam	242	0.061	(0.073)	0.399	(0.098)	-1.954	(0.73)	0.168	(0.13)	1.081	(0.92)	0.568	(0.21)	-0.371	(0.84)
L Sand	201	0.049	(0.042)	0.390	(0.070)	-1.459	(0.47)	0.242	(0.16)	2.022	(0.64)	1.386	(0.24)	-0.874	(0.59)
Sand	308	0.053	(0.029)	0.375	(0.055)	-1.453	(0.25)	0.502	(0.18)	2.808	(0.59)	1.389	(0.24)	-0.930	(0.49)
S Clay	11	0.117	(0.114)	0.385	(0.046)	-1.476	(0.57)	0.082	(0.06)	1.055	(0.89)	0.637	(0.34)	-3.665	(1.80)
S C L	87	0.063	(0.078)	0.384	(0.061)	-1.676	(0.71)	0.124	(0.12)	1.120	(0.85)	0.841	(0.24)	-1.280	(0.99)
S loam	476	0.039	(0.054)	0.387	(0.085)	-1.574	(0.56)	0.161	(0.11)	1.583	(0.66)	1.190	(0.21)	-0.861	(0.73)
Silt	6	0.050	(0.041)	0.489	(0.078)	-2.182	(0.30)	0.225	(0.13)	1.641	(0.27)	0.524	(0.32)	0.624	(1.57)
Si Clay	28	0.111	(0.119)	0.481	(0.080)	-1.790	(0.64)	0.121	(0.10)	0.983	(0.57)	0.501	(0.27)	-1.287	(1.23)
Si C L	172	0.090	(0.082)	0.482	(0.086)	-2.076	(0.59)	0.182	(0.13)	1.046	(0.76)	0.349	(0.26)	-0.156	(1.23)
Si Loam	330	0.065	(0.073)	0.439	(0.093)	-2.296	(0.57)	0.221	(0.14)	1.261	(0.74)	0.243	(0.26)	0.365	(1.42)

The drainage design and seepage inputs are all stored in the .GEN file in DRAINMOD. The drainage design inputs were kept very similar to those in Singh and Helmers (2006). Drainage spacing was adjusted for the simulations in Section 3.4.5 for determining the anthropogenic impacts, but a constant spacing of 20 m was used for all other simulations based on typical values for the main Iowa soils found in the Iowa Drainage Guide (Iowa State University Extension and Outreach, 2012). When modeling an undrained field, the drainage coefficient was simply set to 0 cm/day so that DRAINMOD would calculate the potential drainage of the system without releasing the water from the system because the drainage coefficient is limiting. This is not the original purpose of DRAINMOD, but it fit the need to compare drained and undrained fields. Lateral seepage is another important component in the drainage design section, especially when considering the undrained state. In order to have lateral seepage, a constant head boundary was assumed to be a ditch with a depth of 1.06 m (the same depth as the tile drains) that was located 100 m from the tile drains. This implies that there is either a perennial stream or an aquifer at the edge of the field that does not fluctuate much throughout the year. This constant head boundary allowed for lateral seepage from both drained and undrained fields, but it is also a potential source of error. During dry times, when the water table dips below the tiles due to ET and vertical seepage, the lateral seepage turns negative, which means that water is flowing back into the subsurface. This adds water to the system from an outside source and can alter the water balance, though the impact is minimal. The constant head boundary is the best option available to simulate lateral seepage, and it was necessary for comparison to keep the boundary at the same head as the tile drains and to keep the same head for each soil type.

The crop inputs are the only inputs that were left unadjusted from the original Webster model. The crop inputs (.CIN file) are based on continuous corn (Zea mays L.) cultivation and contain data such as effective rooting depths over time, water excess, and deficit stress factors as well as trafficability parameters and desired planting dates. These factors are important to the use of DRAINMOD because they dictate ET, but they are typically more important for the Relative Yield applications of DRAINMOD. Therefore, these values were kept constant for all simulations because they give a realistic representation of the agricultural practices of Iowa, and adjusting them would add unnecessary complexity to this hydrologic analysis. DRAINMOD inputs for one soil type are located in **Appendix A**.

3.3.3 DRAINMOD Outputs for the Field Scale Analysis

DRAINMOD typically outputs daily, monthly, and yearly data that can be analyzed either with the model's graphing utility or read from the multiple easily-formatted text files, such as the .GRD or .GRM files. However, there is an option in DRAINMOD to obtain either hourly surface runoff or hourly water loss outputs from the model located in the .SRO file. Water loss is defined by DRAINMOD as hourly surface runoff plus hourly tile flow. The purpose of this study is to understand the hydrologic impacts, especially with regard to flooding and peak flows, so the hourly data is used in this analysis. There are two problems with the hourly data outputs from DRAINMOD: 1) the format is very difficult to use, and 2) there are no seepage values included. To remedy the first problem, a script was created in MATLAB to convert .SRO files to a more usable row and column format for analysis. The second problem was more tedious to figure out, and some key assumptions were made. The main interest was in lateral seepage values, because lateral seepage is assumed to be leaving the field and combining with runoff and tile flow. Lateral seepage appears to be calculated on a daily basis, since it is typically very slow, so converting daily lateral seepage values to hourly values would be fairly accurate. However, DRAINMOD does not have lateral seepage values printed to easily usable text files (like the .GRD), so, for simplicity, easily obtainable monthly values of lateral seepage were converted to hourly values and then added to the hourly water loss outputs to create a final output. This assumption causes each month to have a constant lateral flow value, which may affect some of the analysis but, in reality, lateral seepage values do not change much within a month. Also, this method maintains some of the seasonal variability in lateral seepage values, which would be excluded by converting a yearly seepage value to an hourly value. This method of adding a constant hourly seepage per month also reflects one other assumption regarding negative monthly lateral seepage. The negative monthly seepage values typically occur during really dry periods or winter months where the water table dips below the constant head boundary and simulates the water from the head boundary stream or aquifer infiltrating back into the field. The method used for these negative months is that for the hours with water loss, the negative seepage value was removed from the water loss, which mimicked a water exchange at the boundary interface. Lateral seepage was assumed to be zero instead of a negative value for hours with no water loss. This second assumption was made for simplicity of the analysis and could be a potential source of error, but the time of interest for this analysis entails water loss, so this is the portion that was made the most realistic.

3.3.4 Metrics for Analyzing Hydrologic Response

Hydrographs and annual peak discharge were used for this analysis. The hydrographs are hourly outputs (area-normalized) from DRAINMOD, and the annual peak discharge is defined as the maximum hourly discharge for the selected year (mm/hr). In addition, to get a better idea of the impact of subsurface drainage on the entire flow regime, the flow duration curve and the Richard Baker Flashiness Index was used. The flow duration curves (FDCs) were estimated using the daily mean flow data (mm/hr), as recommended by the USGS (Searcy, 1959). The Richard-Baker Flashiness Index (FI) is a measure of flow oscillations relative to total flow and is a good indicator of how quickly a system responds to a hydrologic input. **Equation 3.11** is the FI:

$$R - B\ Flashiness\ Index = \frac{\sum_{i=1}^{n} |q_i - q_{i-1}|}{\sum_{i=1}^{n} q_i} \quad (3.11)$$

where q_i is the flow at a time step (i), q_{i-1} is the flow at the previous time step (i-1), and n is the total number of time steps. The FI is typically used with mean daily flow data, but there are some uses at smaller scales with hourly data when it is important to capture diurnal variations (Deelstra & Iital, 2008). For this analysis, mean daily data (mm/hr) were used in order to have consistency with the FDC analysis and because it was thought to be less sensitive to the constant lateral seepage assumption. The peak flow and FI results are visualized in the analysis with boxplots created with the statistical software R. Additionally, significance testing for differences between the results of drained and undrained fields was performed in R using the one-tailed t-test, assuming unknown and unequal variances, which has the following test statistic and degrees of freedom:

$$T' = \frac{(\bar{X}_1 - \bar{X}_2) - (\mu_1 - \mu_2)}{\left({\hat{S}_1}^2 / n_1 + {\hat{S}_2}^2 / n_2 \right)^{0.5}} \tag{3.12}$$

$$v = \frac{\left({\hat{S}_1}^2 / n_1 + {\hat{S}_2}^2 / n_2 \right)^2}{\frac{\left({\hat{S}_1}^2 / n_1 \right)^2}{(n_1 - 1)} + \frac{\left({\hat{S}_2}^2 / n_2 \right)^2}{(n_2 - 1)}} \tag{3.13}$$

where *T'* is the test statistic, $\bar{X}_1$ and $\bar{X}_2$ are the sample means of the data, ${\hat{S}_1}^2$ and ${\hat{S}_2}^2$ are the sample variances of the data, $\mu_1 - \mu_2$ is assumed to be zero according to the null hypothesis, n_1 and n_2 are the number of data points, and *v* is the degrees of freedom to be used when looking up the critical t-value from the studentized t-distribution (Kottegoda & Rosso, 2008). This significance test is used because it is the most general case and allows for the least number of assumptions about the data. Each test significance test was performed at a significance level of 0.05.

3.4 Results of Numerical Experiments

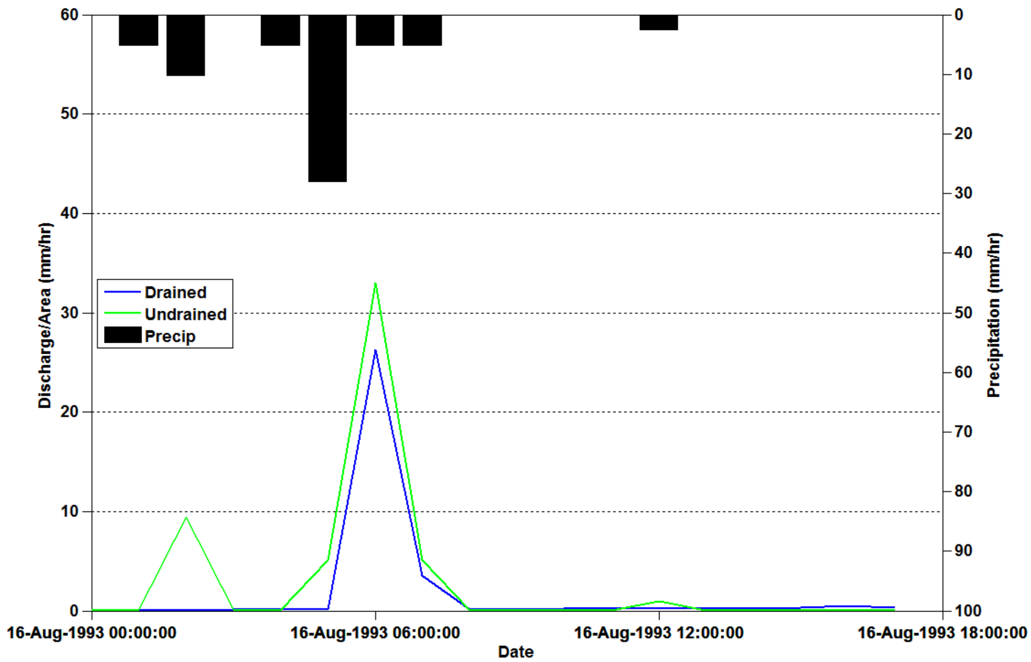
3.4.1 Impacts of Landscape Controls: Soil Type and Surface Storage

3.4.1.1 Soil Type Impacts

One major landscape control that influences the hydrologic response of tiles at the field scale is soil type. There are 30 years of available simulation data, but for succinctness, event hydrographs will only be analyzed from 1993, which was a year of prevalent flooding in Iowa. In the literature, the conclusion was posed that tile drainage can reduce peak flows in soils that had frequently inundated pre-drainage condition and increase flows in more permeable soils that were subsurface flow dominated before drainage. Below (**Figure 3-7**) are the hydrographs for clay, sand, and loam for a fairly large August 1993 event that examine whether this behavior is valid. The loam is fairly representative of how silt, silt loam, and silty clay loam respond to the precipitation event. All three soils show a decrease in the peak flow with the addition of tile drainage. This is expected for the more poorly drained clay and loam soils but not for the sand. The reason this happens is because the event is so large that under undrained conditions the flow is dominated by surface runoff regardless of soil type and tile drainage. However, due to the water table being at the drain level in the drained sand scenario, all the water is allowed to infiltrate rather than run off given the high infiltration capacity of sand. A similar mechanism occurs in the clay and loam soils: potential surface runoff is allowed to infiltrate, thereby reducing the peak flow.

To check, the cumulative discharge was examined to ensure that the areas under the hydrographs are similar. Since the sand is the most extreme scenario, with an essentially flat hydrograph for the drained field during the event, it was analyzed to ensure that the water balance is reasonable. **Figure 3-8** shows that the water balance is reasonable for the time period of the hydrograph in **Figure 3-7 B**. During this event, the

A) Clay



B) Sand

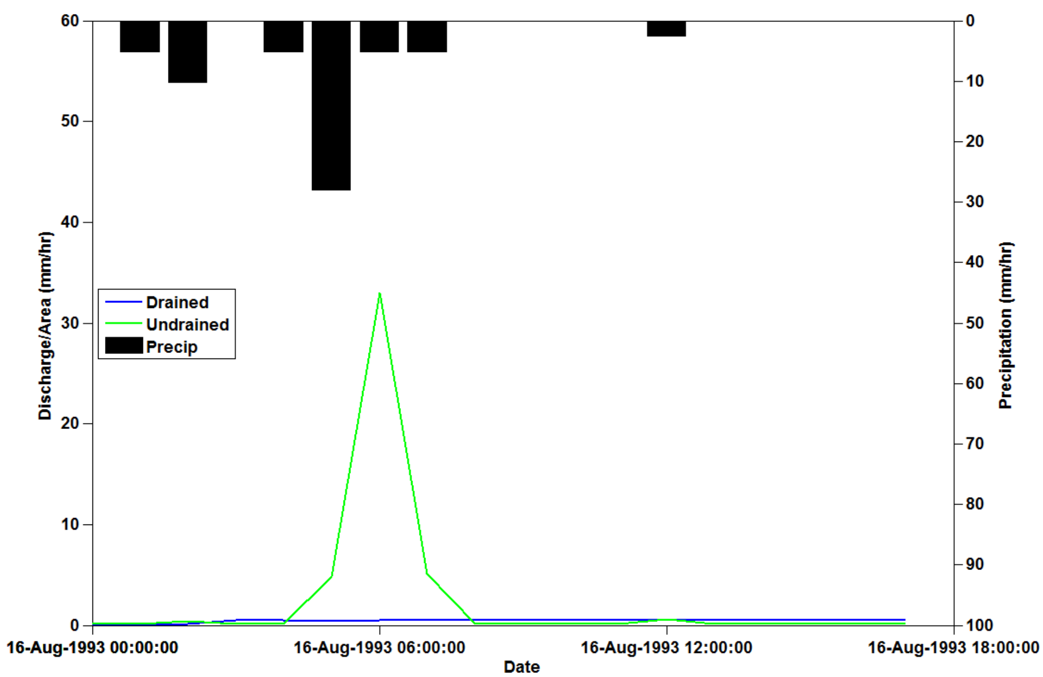


Figure 3-7 - Drained and undrained hourly hydrographs for an August 1993 event for three soil textures.

C) Loam

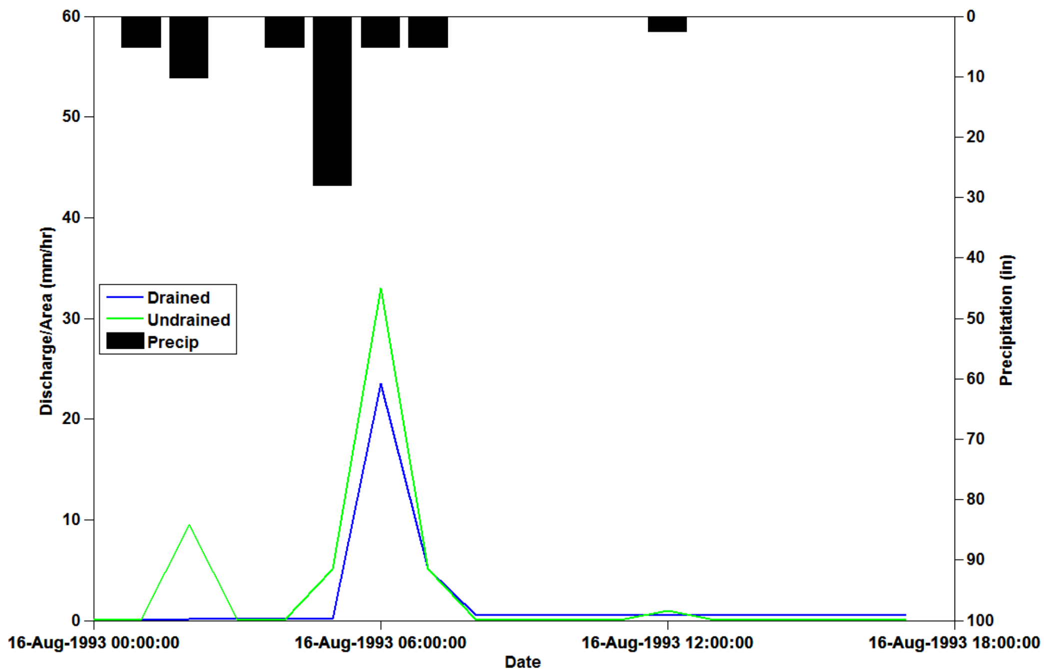


Figure 3-7 continued

drained sand water table was below the tiles, so there is water unaccounted for in the cumulative discharge plot due to deep subsurface storage. The hydrograph analyses indicate that for large events tiling can reduce the hourly peak flow for all soil types.

The annual peak discharges were analyzed for the six different soil types for years 1981 - 2010 to explore whether the results observed above are consistent across all storms. **Figure 3-9** contains the boxplots of the 30 annual peak discharges for the six soil types. The peak flows were not statistically different for the undrained vs. drained scenarios for any of the six soil types. The reason behind this behavior is that the largest storms of the year are almost always dominated by surface runoff. The magnitude and intensity of the event is so large that the subsurface moisture deficit has practically no effect on peak flow. Thus, for these storms, tile drainage has no effect on hydrograph response.

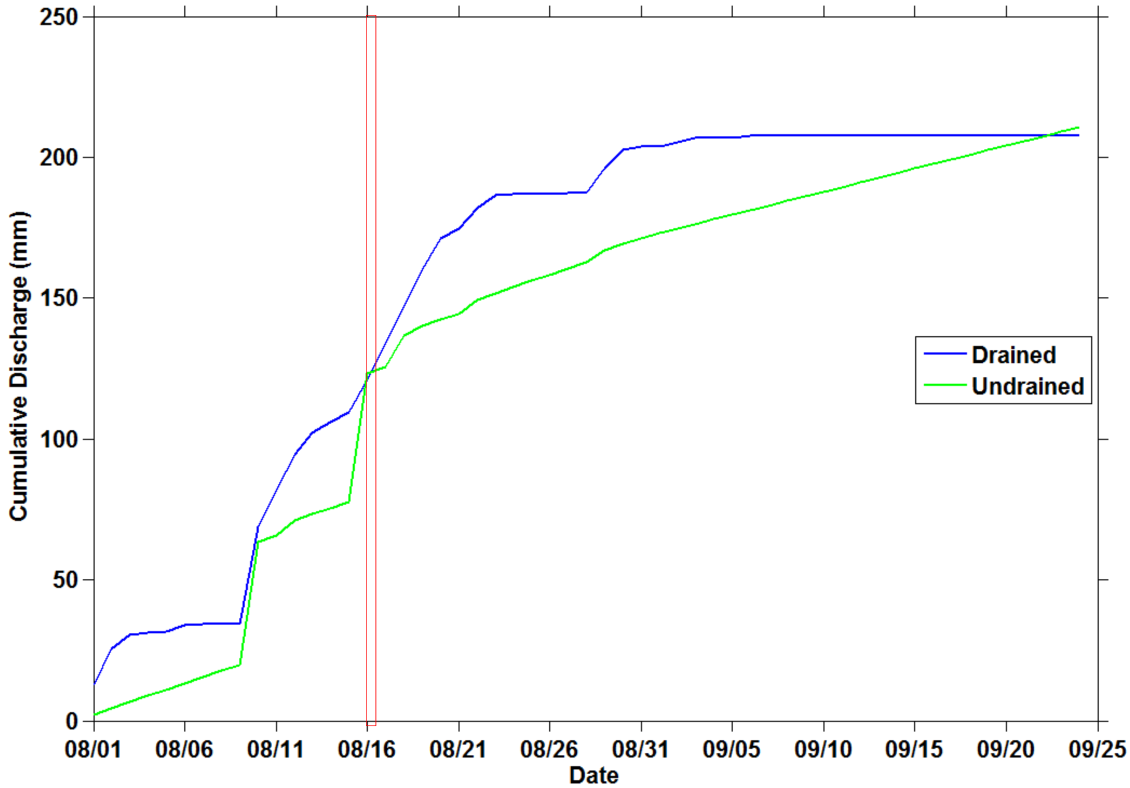


Figure 3-8 - Cumulative discharge for sand drained and undrained fields during August 1993. The red box indicates the time frame of the storm event analyzed in the above figure.

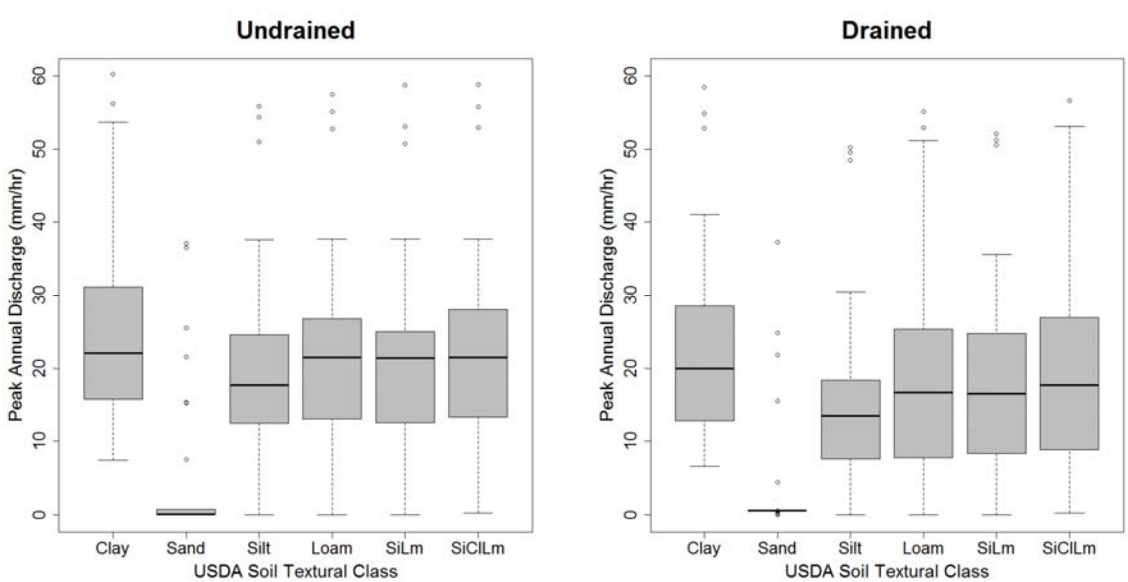
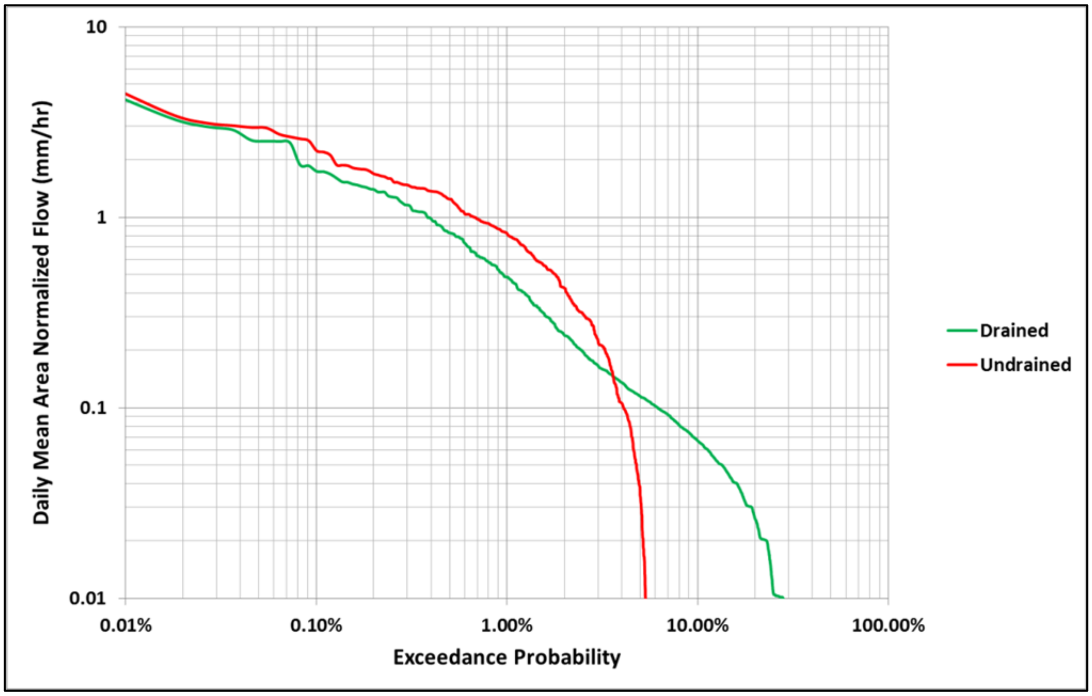


Figure 3-9 - Peak annual discharge from 1981-2010 for six soil types in the drained and undrained state.

The flow duration curves for the two end member soil types, clay and sand, explain the behavior of flow regime shifts with drainage in **Figure 3-10**. For flows with less than 4% exceedence probability (EP), the clay drained soil exhibits lower flows than the undrained scenario. This is because in drained soils there is available subsurface storage that reduces the amount of fast surface runoff. At much lower exceedence probabilities (<0.03%), the difference between the drained and undrained events is less because these events are much larger and are dictated more by a storm's volume and intensity. At greater than 4% exceedence probability, there are low flow events which are greater for drained fields. These events are either the result of smaller, less intense rainfall events which allow infiltration in both the drained and undrained state of clay soil or are the baseflow portions of larger storm events. Once the subsurface is the primary flow path, the tiles move water more effectively than the lateral seepage.

The behavior of the sand field is slightly different, and for good reason. During very low events (>10% EP), the undrained sand actually has a higher flow. This can be attributed to the water table being around the tile level in the drained fields and higher in the undrained fields during very small precipitation events or dry times. The water infiltrates in both fields, but the higher head of water driving the lateral seepage creates greater flow than the small amount of head above the tiles. These flows are very small and probably not all that significant. Then, between 10% and 0.2% EP, the drained fields actually have higher flows. The high infiltration rates of the sand fields do not allow much surface runoff during these events, and the tile subsurface pathway is faster than lateral seepage. Then, at less than 0.2% EP, surface runoff finally starts to dictate and tiling decreases the flows for these large storm events. These results are more in line with those found in literature where tiling increases flows in sandy soils for some storm events, but during very large precipitation events, sandy soils act like clayey soils.

A) Clay



B) Sand

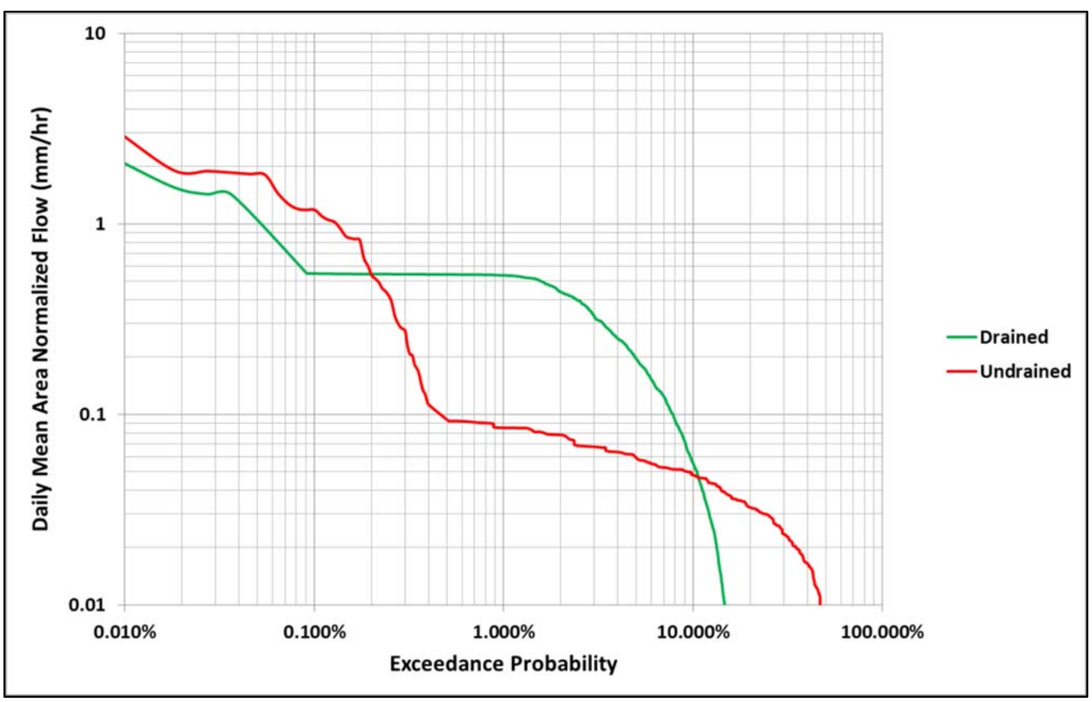


Figure 3-10 - Flow duration curves using daily mean flows (mm/hr) from 1981-2010 for two extremes soil textures.

The Richard-Baker Flashiness Index (FI) also gives a better idea of the impact of soil type on tiling's response and allows for statistical inference. The daily mean FI values are plotted below in **Figure 3-11**. The plot indicates that tiling reduces the FI in clay, silt, loam, silt loam, and silty clay loam while increasing the FI in sand. The differences between the FI for drained and undrained fields is statistically significant at the 5% level for all comparisons. These results seem to corroborate conclusions in the literature that drainage in soils that were surface runoff dominated can have peak reduction, whereas soils that were subsurface flow dominated (like sand) can actually have higher peaks with the addition of drainage (Robinson, 1990; Robinson & Rycroft, 1999). The events located at 0.2% and 10% EP in Figure 3-10B are increasing the FI because most water is infiltrating regardless of drainage, so the addition of drainage increases the mean daily flow, as compared to lateral seepage in undrained fields. The values for the more poorly drained soils expectedly decrease in flashiness with drainage because surface runoff is being reduced. All of the mean daily FI and the p-values from the significance testing for the annual peak discharge are shown below in **Table 3-2**.

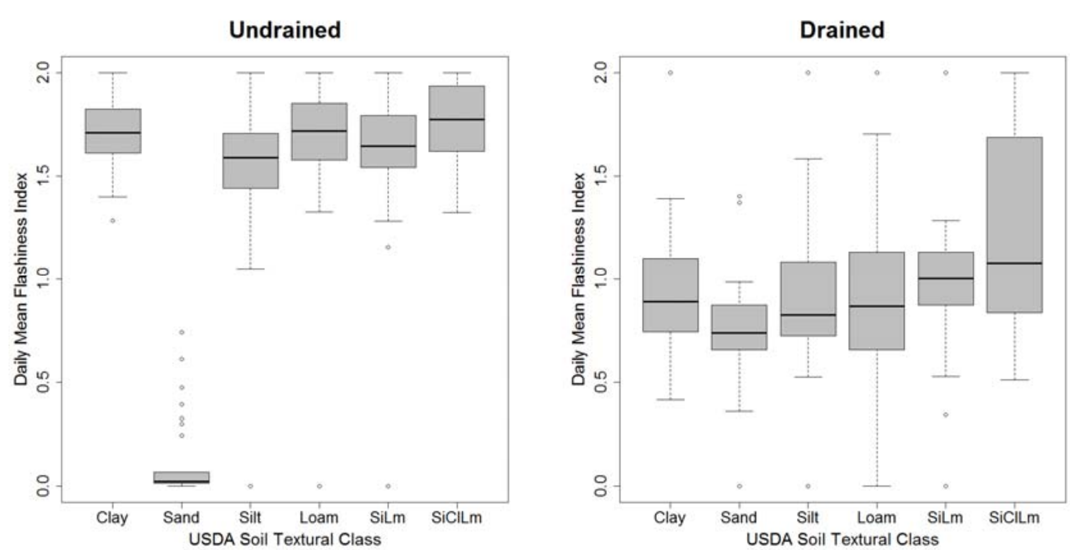


Figure 3-11 - Flashiness index of drained and undrained for six different soil types at the daily time scales.

Table 3-2 - P-values for the one-tailed t-test that evaluates the difference between drained and undrained fields for 30 years of hydrologic data and six different soil textures at a 5% significance level.

Soil Type	Annual Peaks	Daily Mean Flashiness
Clay	5.34E-01	2.04E-11
Sand	5.63E-01	1.54E-13
Silt	3.17E-01	3.02E-04
Loam	4.27E-01	4.75E-07
Silt Loam	3.86E-01	4.37E-05
Silt Clay Loam	5.17E-01	1.36E-06

These simulations were all run with a constant surface storage representation, which could be an inaccurate assumption. Typically, different fields could have various surface storage values based on land use and topography. Therefore a sensitivity analysis was performed in order to understand the impact of the surface storage parameter on the results seen in this section.

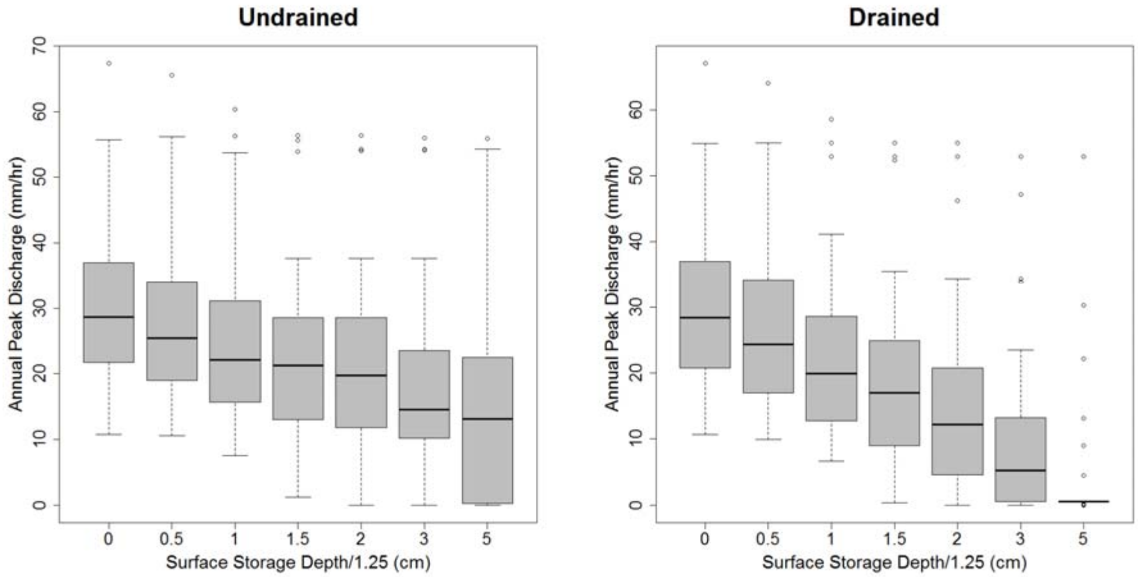
3.4.1.2 Surface Storage Capacity

The original surface storage depth was 1.25 cm for the area normalized DRAINMOD representation of a field. In order to evaluate the effect of surface storage, six additional surface storage depths (0, 0.625, 1.875, 2.5, 3.75, and 6.25 cm) were selected. The annual peak discharge and mean daily Flashiness Index were the metrics used to analyze clay, sand, and loam.

The peak flows for the three soil types at the seven different surface storage depths are plotted in **Figure 3-12**. The results are as expected for all three soil types: the greater the amount of surface storage, the greater the reduction in peak flows. This is simply because water is allowed to remain on the surface longer and can infiltrate into the subsurface and leave by either tile drainage or lateral seepage, which is a slower flow path than surface runoff. The sand results are different from the clay and loam results because sand had very low average peaks due to the high infiltration rates. However, notice how the number of outliers (dots) in the sand plot decreases with more storage. This decrease means that all water is infiltrating and being routed through tiles at high storage, making it difficult to determine whether or not the average annual peak discharge is reduced or increased by drainage in sand in this scenario. Additionally, there are only statistically significant differences in the clay and loam soils between the drained and undrained fields during the 3 and 5 times surface storage scenario. It is during these extreme surface storage scenarios that many of the years will have no surface runoff due to the increased infiltration that results from water remaining on the surface and tile drainage, which brings the overall mean down. The p-values for the t-tests can be found in **Table 3-3**.

The FI for the same soil types and surface storage scenarios were analyzed to give a better idea of the impact of surface storage on the overall flow regime (**Figure 3-13**). Clay and loam, once again, behave similarly with increased surface storage, which causes only a small decrease in the undrained state FI but creates a large difference in the drained state. This may be unexpected because, intuitively, water being held on the surface longer would greatly reduce the flashiness of a field due to water being routed through the subsurface. There are two things to consider when looking at this result. First, clay and loam are not very permeable, so the water that is stored on the surface remains there for a longer period of time for the undrained state than for the drained state. Therefore, surface runoff events still occur in the undrained state while water is infiltrating slowly into the saturated subsurface, while surface runoff is reduced due to increased infiltration in the drained state. Second, the FI is a measure of the total path length of the hydrograph divided by the total flow, so, although the peaks are reduced for these soils with greater surface storage, the total amount of flow in the time period may also be decreasing because water is being stored for long periods of time in the surface and subsurface. This means the ratio could be relatively unchanged.

A) Clay



B) Sand

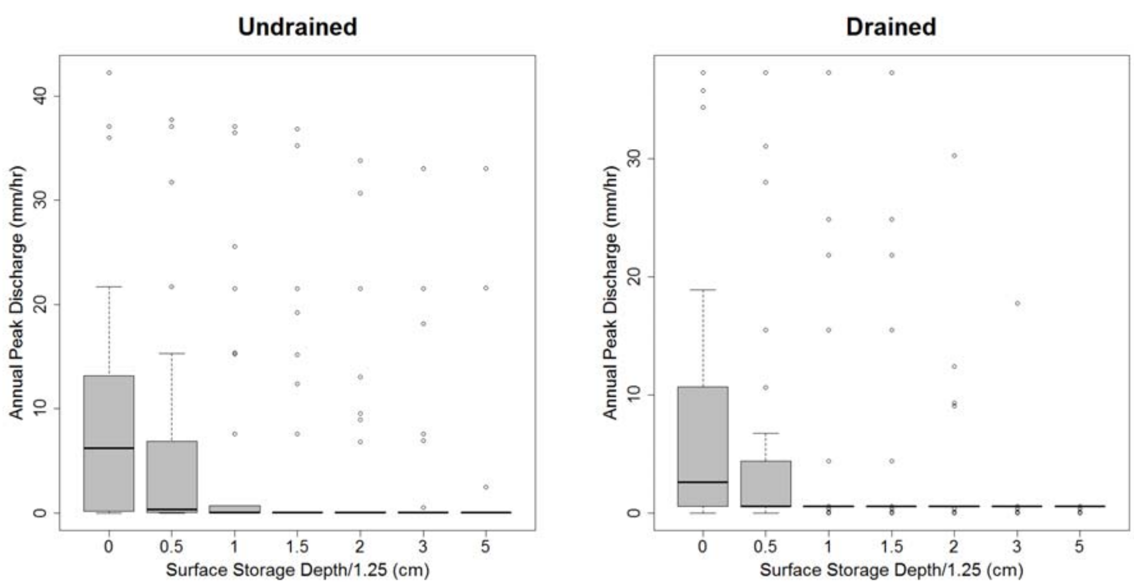


Figure 3-12 - Annual peak discharge for different surface storage scenarios for three soil types.

C) Loam

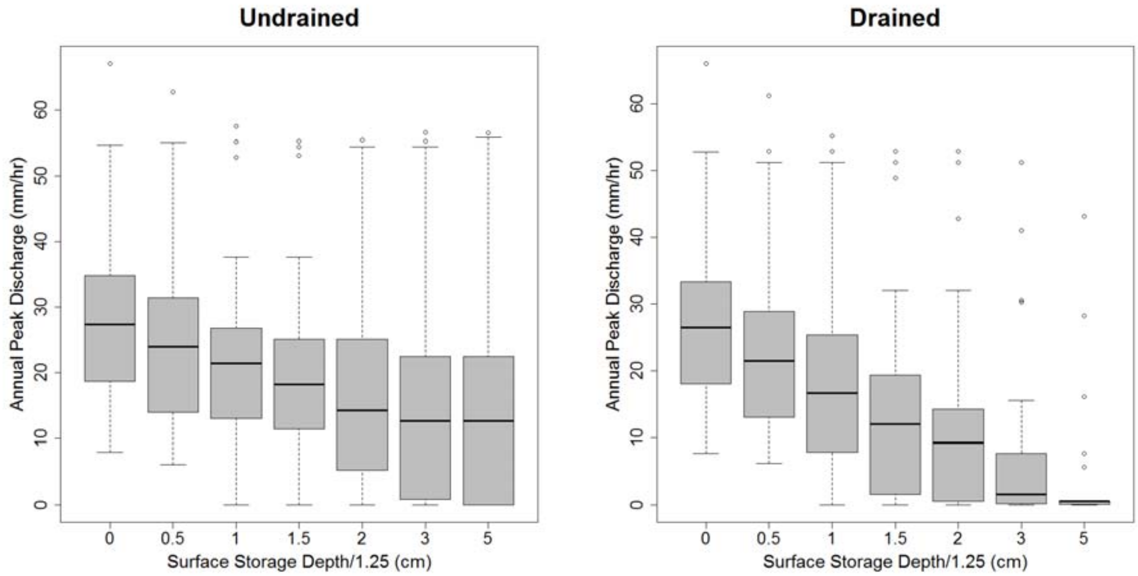
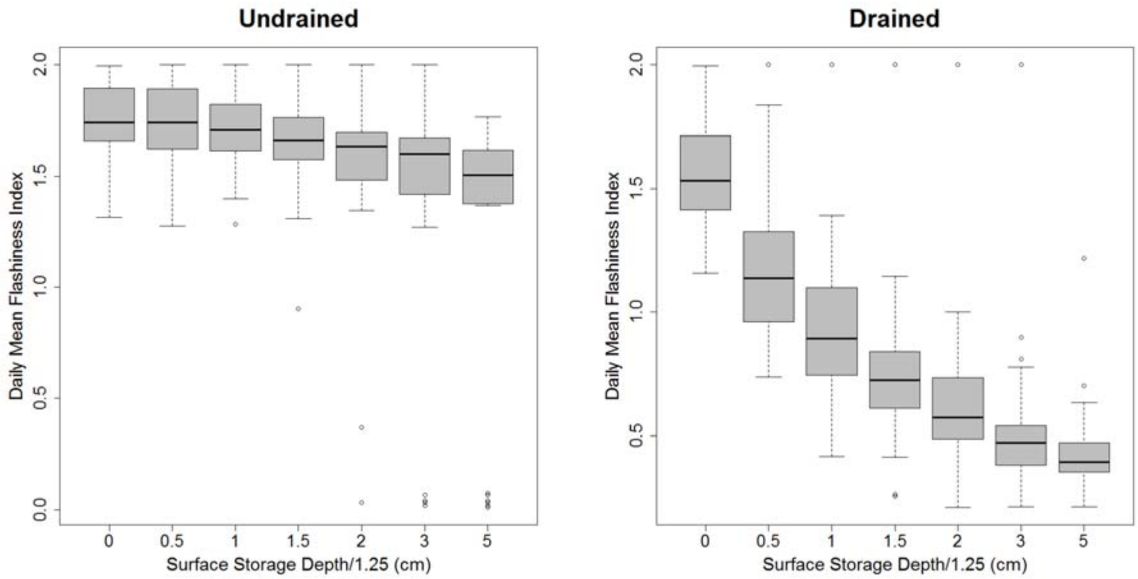


Figure 3-12 continued

Table 3-3 - P-values for the one-tailed t-test that reflects the difference between the drained and undrained fields for annual peak discharge under different surface storage scenarios at a 0.05 significance level.

Surface Storage/1.25 cm	Clay	Sand	Loam
0	0.4743	0.2874	0.4247
0.5	0.4053	0.2835	0.3208
1	0.2670	0.2817	0.2135
0.5	0.1645	0.3305	0.1295
2	0.1201	0.1960	0.0734
3	0.0216	0.1103	0.0096
5	0.0008	0.1350	0.0003

A) Clay



B) Sand

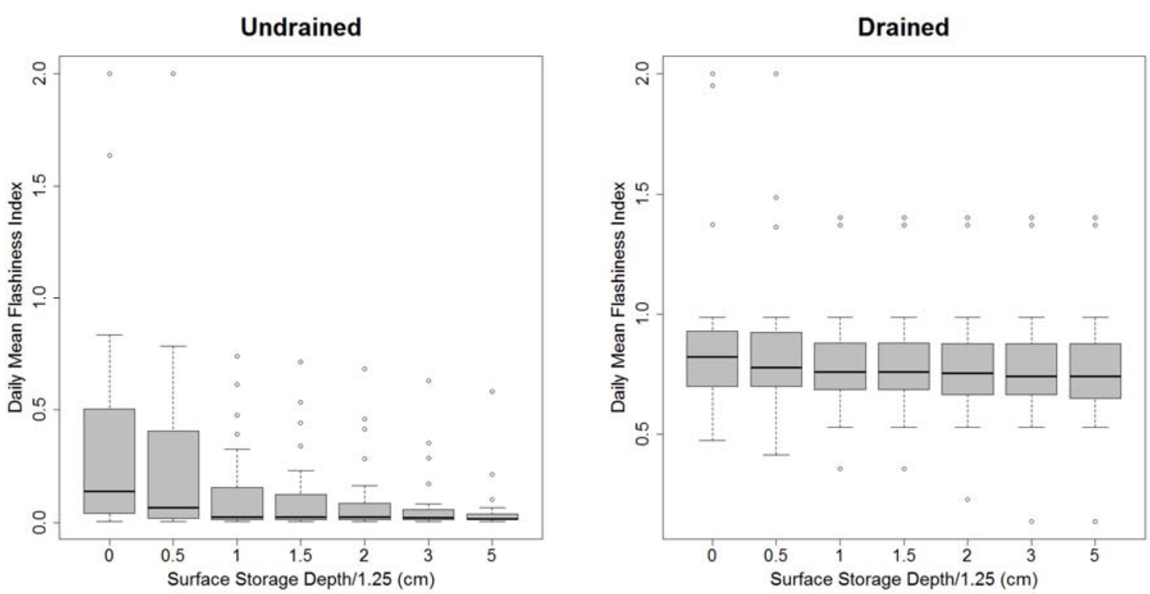


Figure 3-13 - Mean daily Flashiness Index for different surface storage scenarios for three soil types.

C) Loam

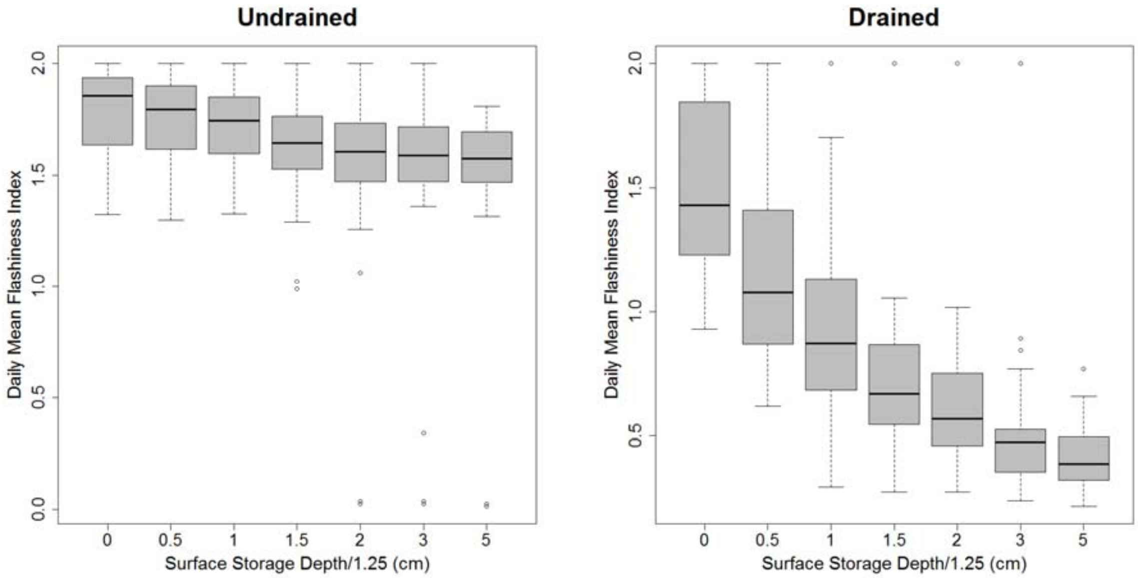


Figure 3-13 continued

The FI for sand follows a different pattern than the other two soils. For the undrained fields, the increase in surface storage causes a rapid decrease in flashiness because more water is infiltrated and leaves via lateral seepage. However, in the drained scenario, the average FI is relatively invariant with surface storage depth. This indicates that the FI is driven by the tile flows from the drained fields. There was rarely surface runoff in the original scenario (1.25 cm surface storage) from the sand fields with drainage because the water table is usually low, allowing for a high infiltration capacity. Adding more surface storage is largely insignificant because most of the water was already being routed through the subsurface. The t-tests (**Table 3-4**) indicate that the FIs of drained and undrained fields are significantly different regardless of the surface storage scenario in the same way as in Section 3.4.1.1. Therefore, for these scenarios, less permeable soils have a decrease in flashiness from drainage, and the magnitude of this reduction is sensitive to surface storage. In sandier soils, the decrease in flashiness is less dependent on the surface storage. However, if surface storage were infinitely high, all soils would have higher flashiness from drainage because tiles are a more efficient flow path than lateral seepage with the present model assumptions.

Table 3-4 - P-values for the one-tailed t-test that shows the difference between drained and undrained fields for mean daily FI under different surface storage scenarios at a 0.05 significance level.

Surface Storage/1.25 cm	Clay	Loam	Sand
0	4.40E-04	1.18E-04	5.66E-06
0.5	1.92E-09	5.17E-07	1.53E-08
1	2.04E-11	3.88E-08	4.38E-17
0.5	7.72E-12	6.16E-10	3.70E-18
2	3.66E-11	2.38E-08	1.13E-17
3	6.33E-08	2.96E-09	3.26E-17
5	2.42E-07	1.98E-11	3.86E-17

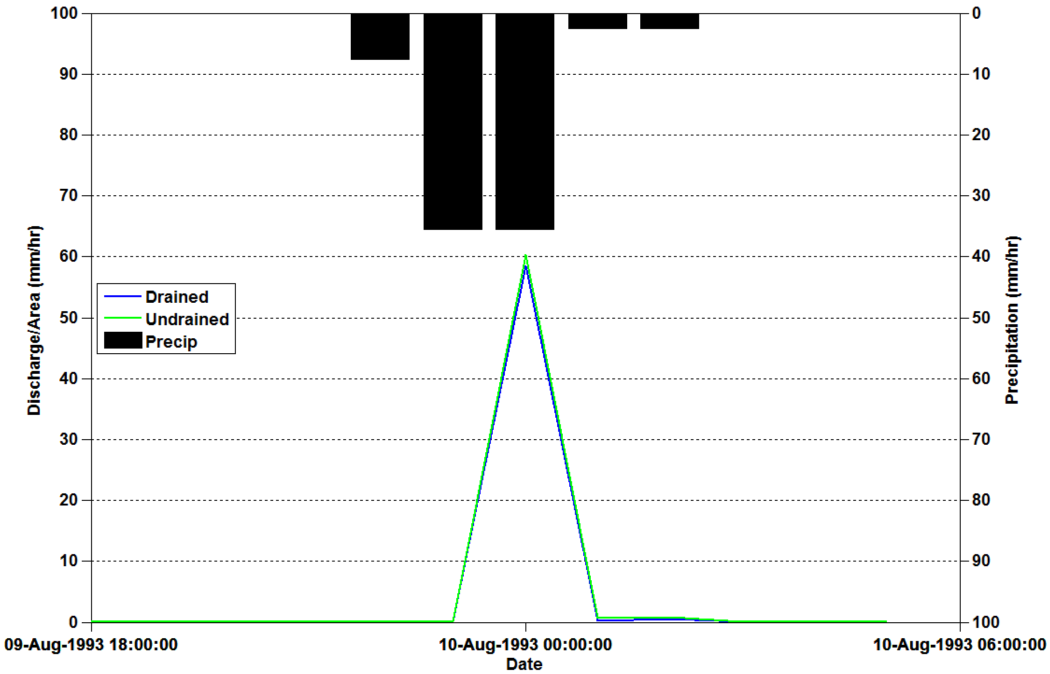
3.4.2 Impact of Climatic Controls: Rainfall

Rainfall is a very important driver of tile's impact on the hydrologic response and can often supersede the impacts of soil type and drainage design for very large storm events. Simply put, if rainfall intensity is much greater than infiltration intensity or if the rainfall volume is much larger than the subsurface storage capacity, there is a point at which the subsurface ceases to be a factor and all water becomes surface runoff. Examining hydrographs of clay, sand, loam, and silt loam soil types during a very large August event helps demonstrate this point in **Figure 3-14**. The clay and loam soils seem invariant to drainage during this very large storm event. The dominant mechanism behind this behavior is surface runoff. Either the infiltration cannot match the rainfall intensity, the subsurface storage is filled, or a combination of the two causes surface runoff. For an extremely permeable soil like sand, the infiltration rate is extremely high and the rainfall rate needed to create this behavior is also extremely high. However, there are realistically no sand fields, in Iowa or anywhere, that need drainage. Silt loam, on the other hand, is more common to Iowa and does have a minor reduction in the peak flow, but the conclusion still holds that the larger the storm event, the less significant the impact of tile drains.

Another method of looking at the impacts of rainfall on the hydrograph is to see how the annual volume of precipitation impacts both the annual peak discharge and the daily mean FI. The annual rainfall amounts are divided into three groups: low, medium, and high, based on the 33rd and 66th percentile. Since there are exactly 30 years of data, there are 10 years in each group. The low rainfall years range from 294 to 683 mm/yr; medium ranges from 684 to 853 mm/yr; and high ranges from 855 to 1504 mm/yr. The results are shown below in **Figure 3-15** and **Figure 3-16** for the peak flows and FI, respectively. Unfortunately, it appears that the annual scale for rainfall amount does not reveal much about the impact of precipitation on tiling. The annual peak flows are higher for clay in the medium and high rainfall years for both drained and undrained, but there is no discernible difference between the medium and high rainfall years in either clay plot. This means that the peaks are more dependent on the characteristics of individual storm events, and annual precipitation volume is not a good proxy for this. The sand plots are also inconclusive for annual peak flows. The means are very low in the sand plots because many of the years have high infiltration and very little surface runoff, yielding low peaks.

The FI separated by annual rainfall types (**Figure 3-16**) explains more about the indicator than the influence of rainfall on tiling's effect on the hydrologic response. For both drained and undrained clay plots, the FI appears to decrease with the higher annual rainfall, which seems counter-intuitive. A simple explanation for this pattern is that years with more rainfall also have more flow, which is in the denominator of the indicator.

A) Clay



B) Sand

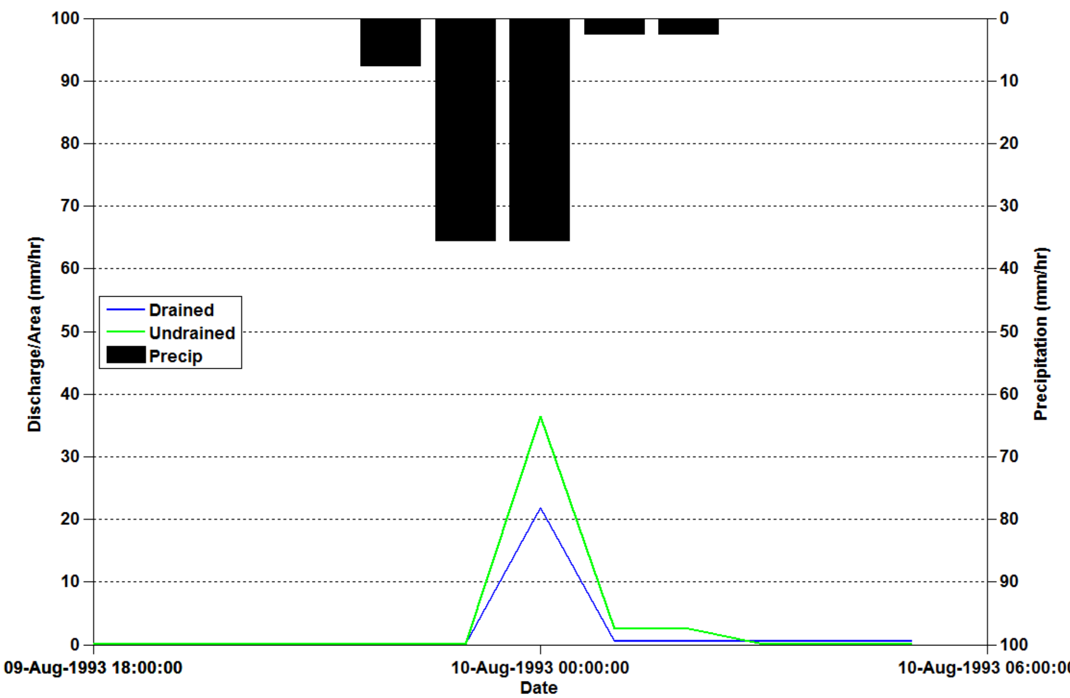
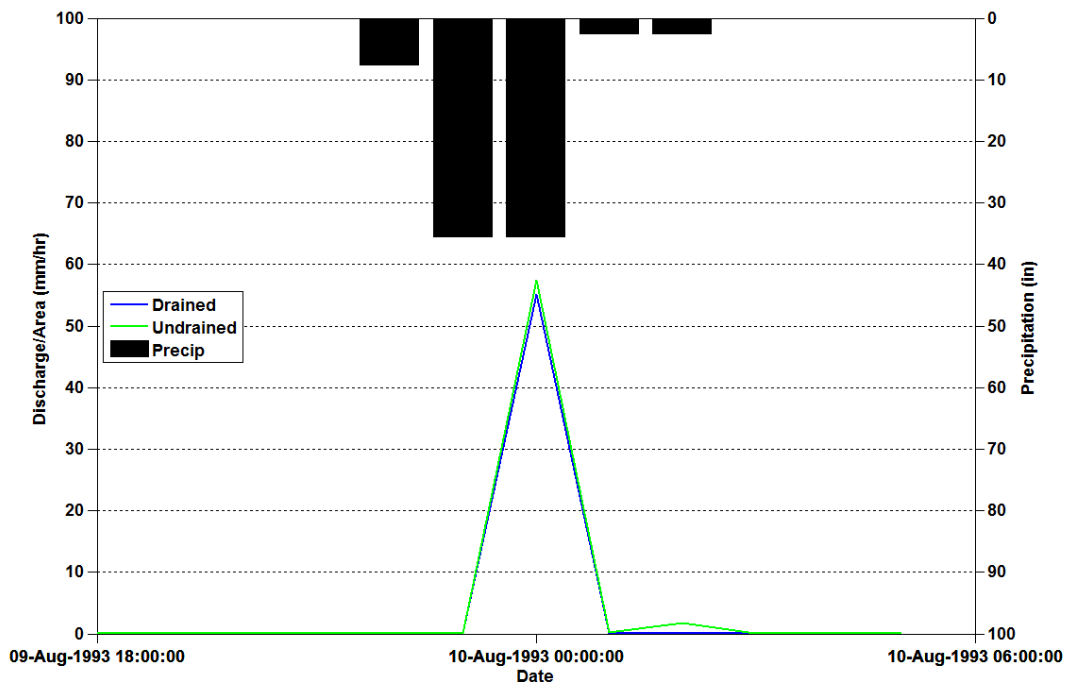


Figure 3-14 - Drained and undrained hydrographs during a large August 1993 event for a wide range of soil textures.

C) Loam



D) Silt Loam

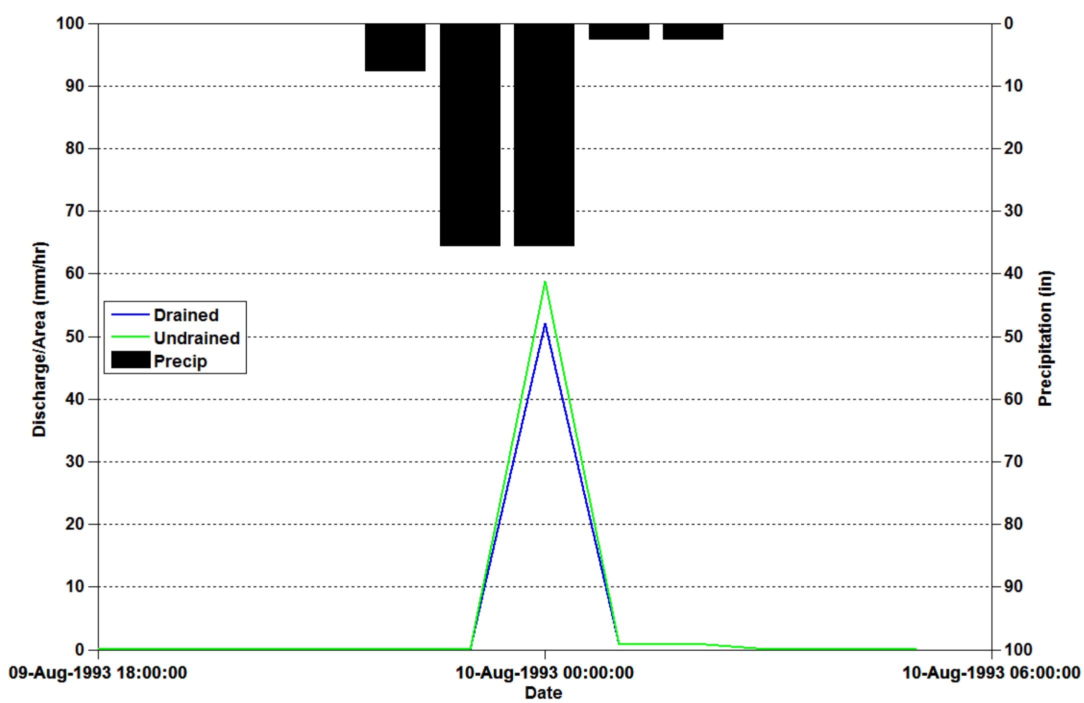
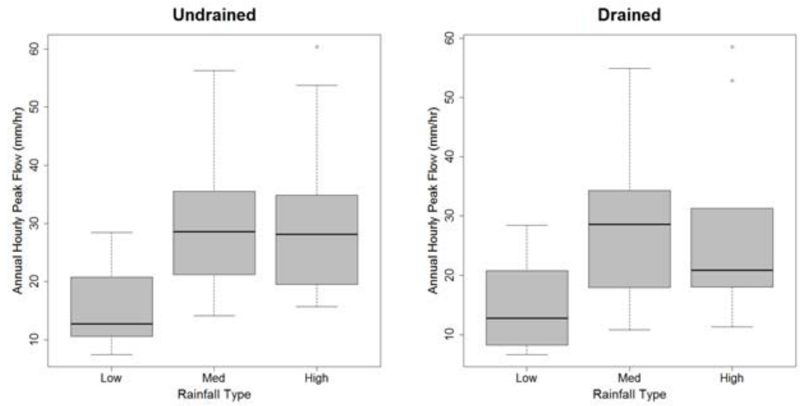


Figure 3-14 continued

A) Clay



B) Sand

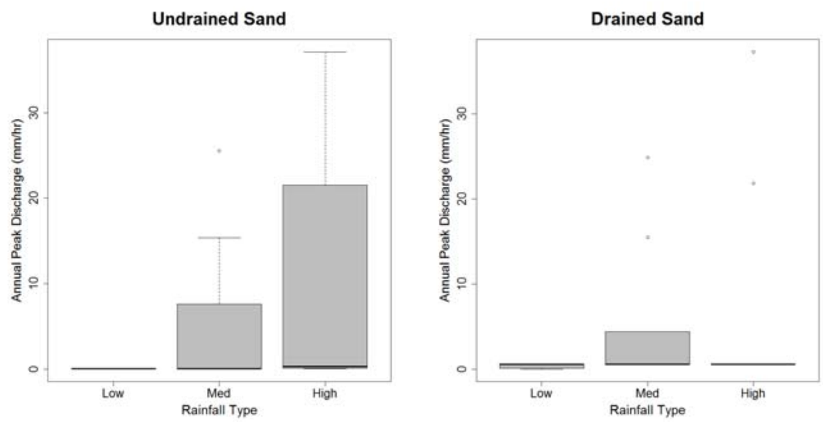
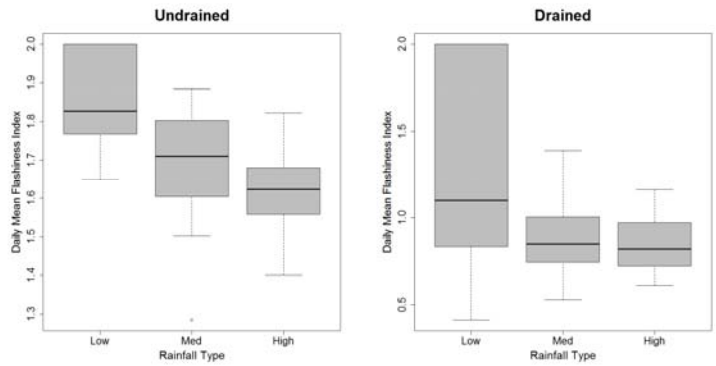


Figure 3-15 - Annual hourly peak flow separated by annual rainfall types for two soils.

Additionally, those years will have slower flows, like lateral seepage and tile flow, which also drive down the indicator. The FI still works well to reflect the impact of drainage on the soil types, with statistically significant differences for all rainfall types between drained and undrained for both clay and sand soils. The sand FI has a very low FI for all years because most water is allowed to infiltrate and leaves via slow lateral seepage. The drained sand plot follows almost the same pattern as the clay plots, where there is more rainfall, there are more flows and the denominator increases, which drives down the FI. The key point to take from these plots is that the FI in low rainfall years is misleading, and annual rainfall does not really help explain the impact of rainfall on tiling impacts.

A) Clay



B) Sand

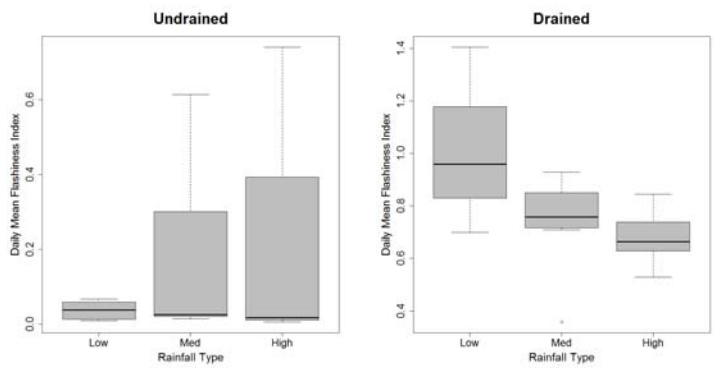
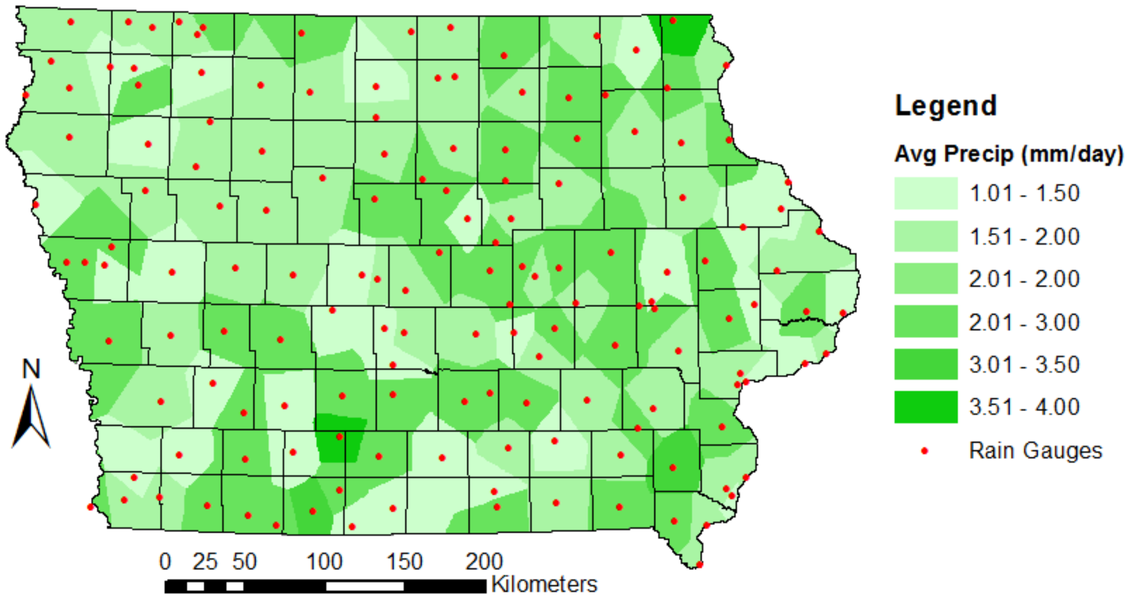


Figure 3-16 - Drained and undrained Flashiness Index separated by annual rainfall types for two soils.

The final rainfall analysis was performed using 30 year normal values for the state of Iowa obtained from the NCDC (NOAA - National Climatic Data Center). The normal data is the 25th, 50th, and 75th percentiles (quartiles) of the daily non-zero precipitation totals of a day from 1981-2010 that are calculated and smoothed using a data from a 29 day window surrounding the day. Readers are referred to the NCDC website for further information on the calculation of normals. In order to do a spatial analysis, Thiessen polygons were created from the 152 rain gauge stations with daily normal data. The constant daily rainfall value used for each polygon was the average daily values for April through September for each quartile. The time period was chosen because it is when the largest amounts of rainfall-runoff events occur. The average Iowa daily normals and rain gauges used are shown below in **Figure 3-17**.

A) 25th Percentile



B) 50th Percentile

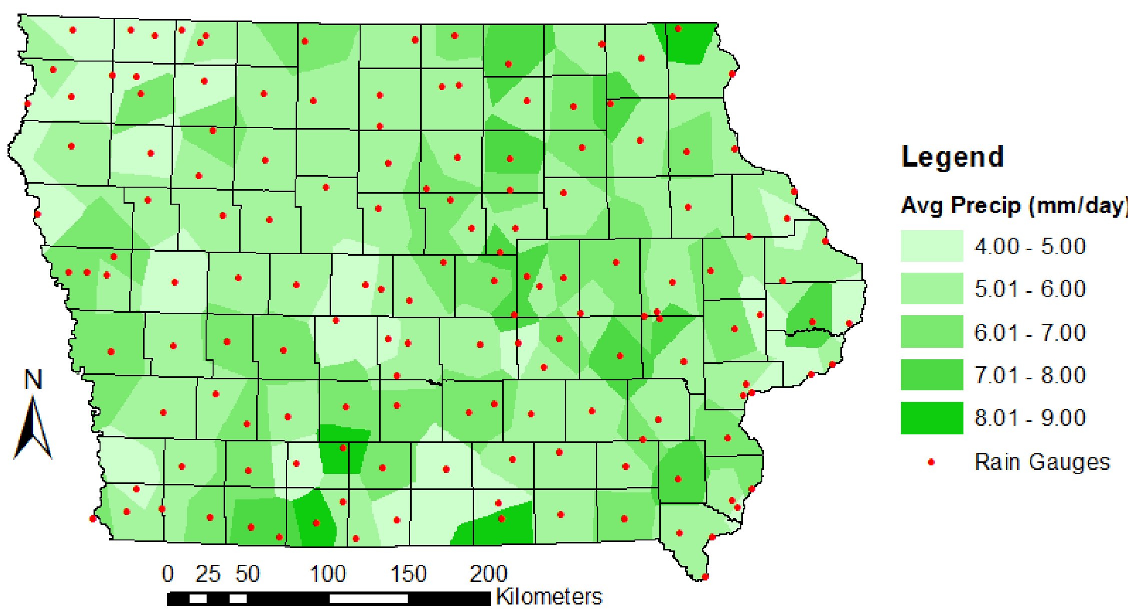


Figure 3-17 - April through September average daily normal precipitation based on NCDC data from 1981-2010.

C) 75th Percentile

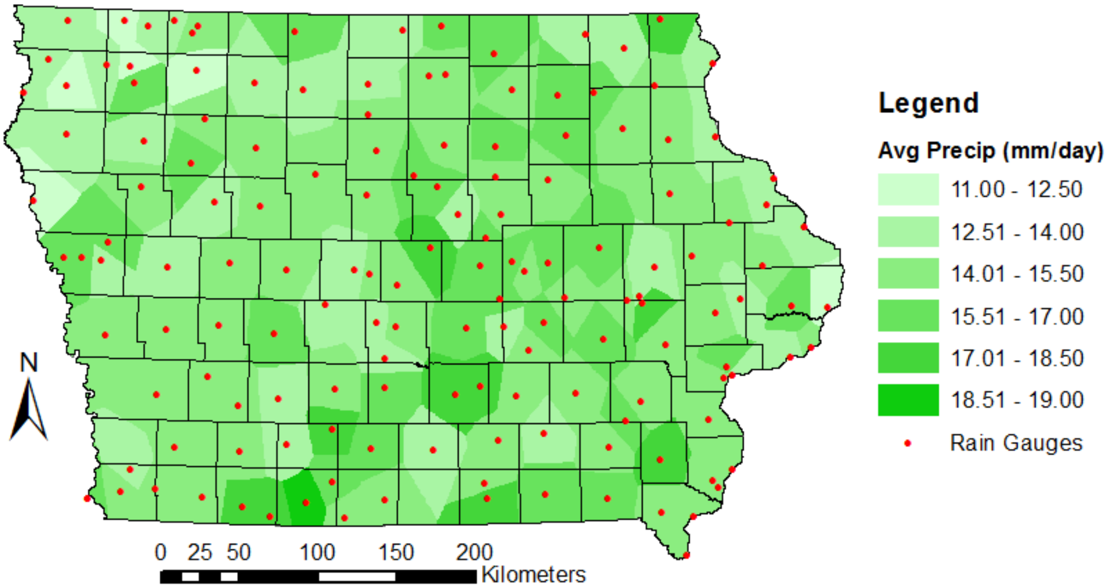


Figure 3-17 continued

The DRAINMOD outputs for the 7 major Iowa soil textural classes (shown in **Figure 3-6 A**) were then analyzed according to their location and the spatial distribution of rainfall normal in Iowa. The daily flow totals were used in this analysis in order to stay consistent with the daily rain data used and the daily analyses in the previous chapters. For each soil type, the flow rates for the drained and undrained field condition were binned and a one-sided t-test was performed between the two datasets to determine whether the undrained scenario's flows were significantly greater than the drained scenario's flows at the 5% level. The hourly precipitation data used in the DRAINMOD simulations made binning easy since they were given in increments of 0.1 inches from the NCDC. However, not all days with precipitation were used in the analysis because some days had either no or very small flows which can greatly impact significance testing. Therefore two separate scenarios were created using flow rate thresholds. The first scenario only used days where the undrained flow rate was greater than 0.1 mm/day, which selects days with significant amounts of surface runoff. The second scenario only used days where the drained flow rate was greater than 0.1 mm/day, which selects days with significant tile flows. The reason for the 0.1 mm/day threshold is to avoid using days that only contained lateral seepage or no flows because lateral seepage required many assumptions and used a monthly value converted to the hourly time scale. Additionally, the days with very low flow rates are not of interest in the analysis of whether flow rates are reduced. Scenario 2 selects a larger amount of data points than Scenario 1 because there are more days where tiles are flowing compared to days with surface runoff. Therefore, Scenario 2 gives a more accurate representation of what is happening at smaller rainfall events where infiltration is allowed. Scenario 1 excludes many of the small flow days and possibly avoids the errors accrued by using these less accurate low flow estimates in significance testing. Therefore, Scenario 1 gives a better representation of larger events that may be infiltration excess because the mean in the t-test is not decreased by the multitude of zero or low flow points.

After the flows are selected and the t-tests are performed, the results need to be represented spatially using the Iowa rainfall normal data. MATLAB and ArcMap 10 were used to achieve this result. A number was assigned to each soil type polygon in each precipitation polygon indicating whether the soil type had a significant increase, decrease or no change in flow for the given average daily rainfall normal. The normal rainfall values for each polygon were rounded to the nearest value at which a significance test had been performed. The results of the significance tests are shown in **Appendix B** and will be discussed later. Below, in **Figure 3-18**, are the results of how daily rainfall normal influence the impact of tile drainage on Iowa soils for both flow threshold scenarios.

A) 25th Percentile

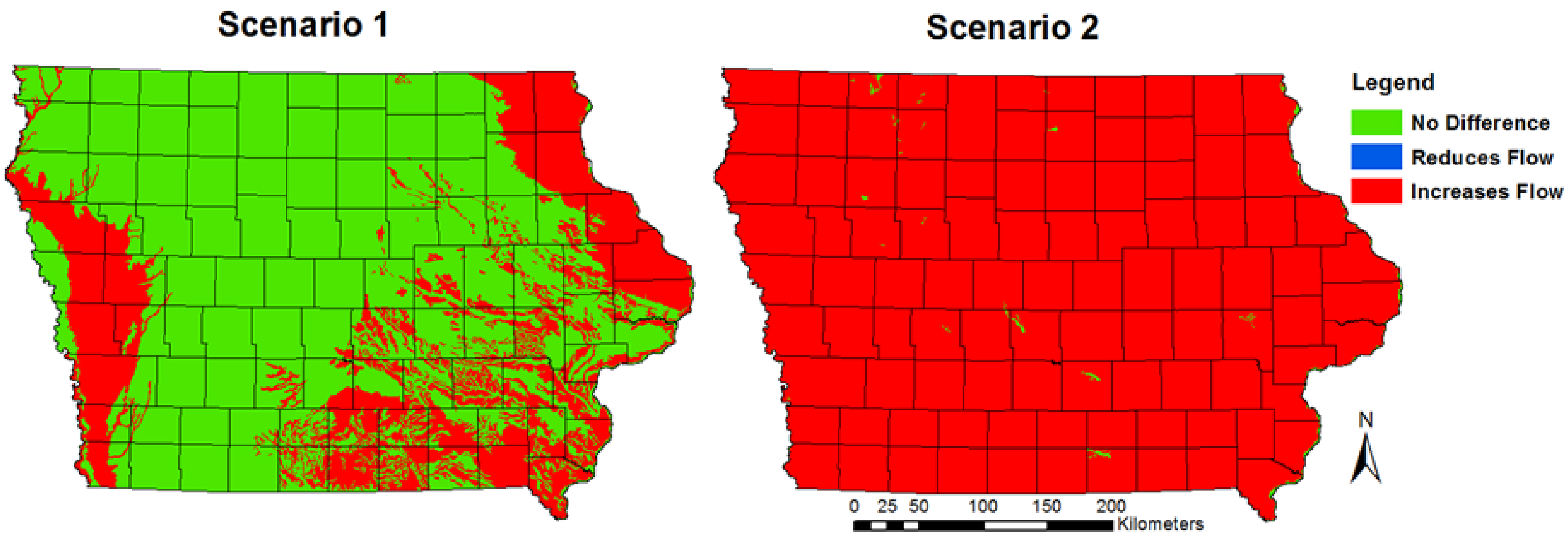


Figure 3-18 - Impacts of tiling based on undrained (Scenario 1) and drained (Scenario 2) flow thresholds for the April through September (1981-2010).quartiles of average daily normal precipitation in Iowa.

B) 50th Percentile

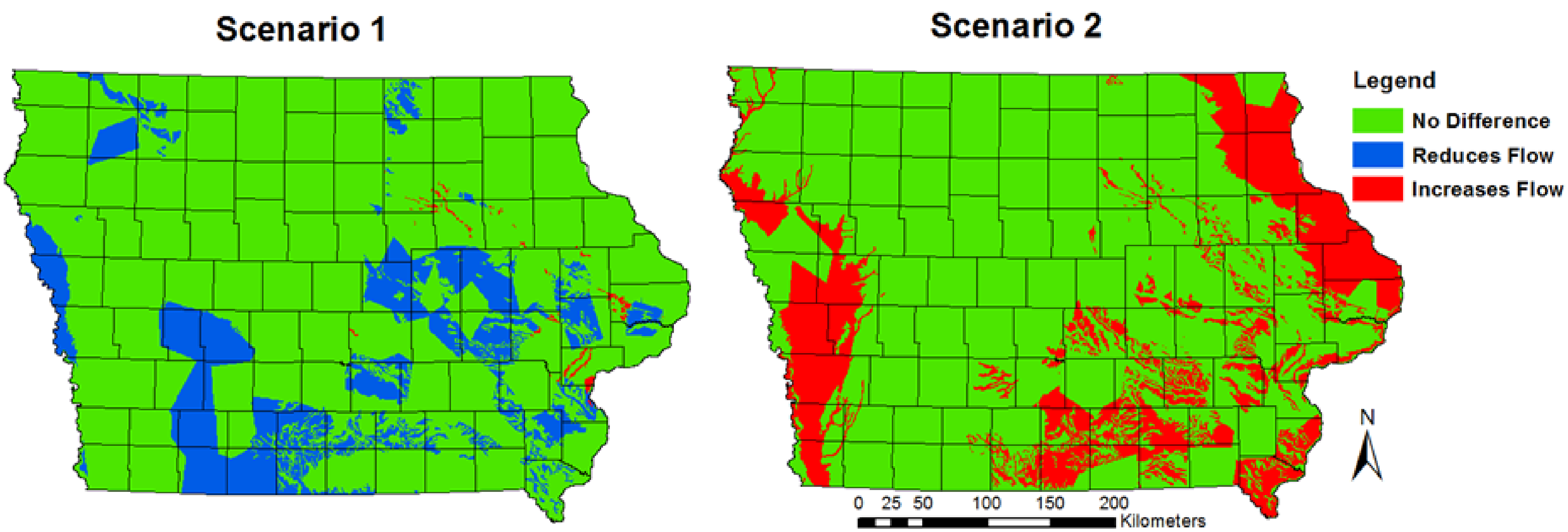


Figure 3-18 continued

C) 75th Percentile

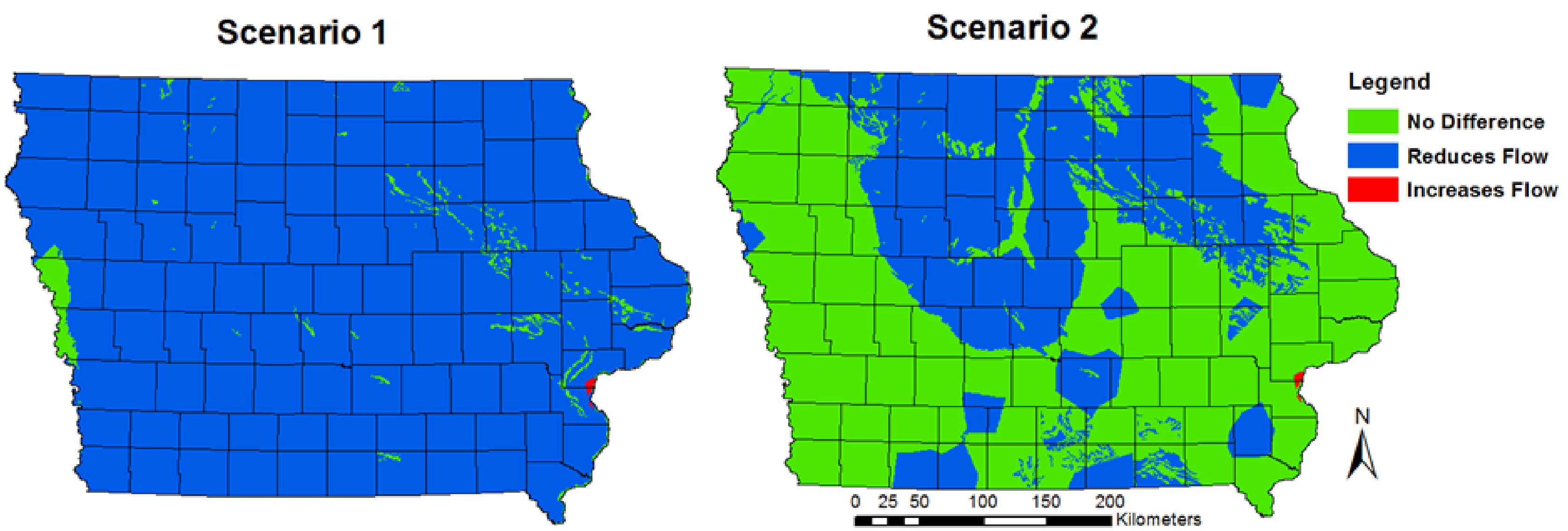


Figure 3-18 continued

The results for the 25th percentile daily rainfall (1-4 mm) indicates that tile drainage can significantly increase daily flows. This is because under such low flow scenarios, most of the precipitation infiltrates and tile drainage is a faster flow path than lateral seepage. The result is more extreme in Scenario 2 because all tile flow days are included which gives a more realistic idea of tile behavior at this rainfall percentile as compared to Scenario 1. The results corresponding to the 50th percentile (4-9 mm) daily rainfall are different for the two scenarios. Scenario 1 indicates that daily peaks are reduced in some of Iowa's loamy soils because surface runoff is reduced. However, Scenario 2 displays some flows still increasing with tile drainage, while others have no difference. The reason for the dichotomy is that in Scenario 2 many low flow scenarios are still selected, which brings mean of both drained and undrained closer to 0 and one another. Alternately, Scenario 1, analyzes only events that have surface runoff, therefore, depending upon which storm events are of interest, different conclusions can be drawn. The results for the 75th percentile (11-19 mm) daily rainfall emphasizes that tile drainage reduces daily flows for large portions of Iowa because the surface runoff is being rerouted through the slower subsurface. The reduction result is, once again, more pronounced in Scenario 1 because of the exclusion of low flow events, but both maps give a similar conclusion.

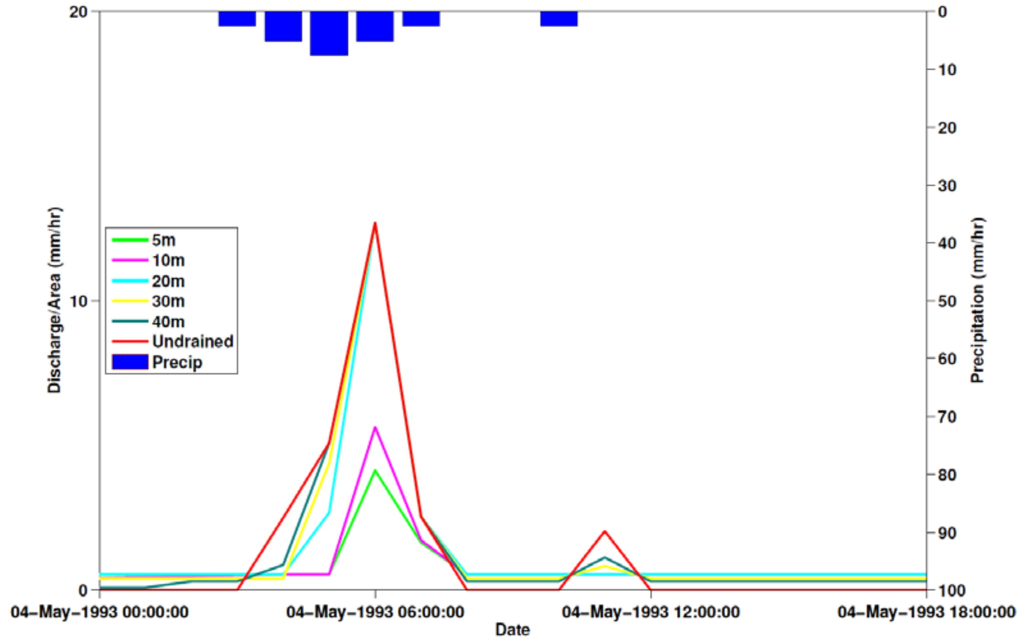
The p-values for each of the soil type for daily rainfall values ranging from 2 to 87 mm are located in **Appendix B**. There appears to be daily precipitation threshold around 30 to 35 mm at which tile drainage significantly reduces daily flows for most soils. For flows around and below this threshold, tiles allow potential surface runoff to be stored in the subsurface and released slowly. However, around 2-4 mm/day of precipitation indicates tiling will increase peak flows as mentioned above. It is difficult to make conclusions for higher daily rainfall amounts because there are fewer samples from the 30 years of DRAINMOD simulations for those events, making statistical inference weak or implausible. However, upon visual inspection many of the flows for larger events were similar supporting the conclusion that at certain rainfall amounts the surface runoff mechanism dominates because subsurface storage is filled or infiltration rates are exceeded.

3.4.3 Anthropogenic Impacts: Drain Spacing

Finally, the effect of drainage spacing on hydrologic response was explored. For all previous simulations, the assumption was made that tile drains are spaced 20 m apart based on typical values found for Iowa Soils in the Iowa Drainage Guide. For this analysis, drain spacings of 5, 10, 30, and 40 m were added to the previous results of the 20 m spacing and undrained fields. Below, in **Figure 3-19**, are the hydrographs for both clay and sand for a smaller storm event in May 1993. As expected, the closer the drain spacing in the clay soil, the more the hydrograph becomes stretched and the larger the low flow rates become (indicated by the 5m spacing). This decrease in peak and increase in low flows may not seem significant, but it will affect the FI values, as seen in the following figures. The sand, in contrast, does not seem to be impacted much by tile spacing since it is so conductive. Any tiles reduce the flow compared to the undrained state to the same level.

The annual peak discharges and FI were also analyzed for the different tile spacings. The results indicate that peak flows are not significantly affected by drain spacing, regardless of soil type (**Figure 3-20**). This could support the theory that many of these events are surface runoff dominated because, regardless of spacing, the peak flows do not change much. The FI (**Figure 3-21**) tells a more interesting story than the hydrographs and peak flows. For clay soils, there appears to be a saddle shape or an optimum spacing at which the FI is at its minimum. In undrained soils, or for large drain spacings, discharge is dominated by surface runoff, leading to the large FI value. As drain spacing decreases, more flow is routed through the subsurface due to increased available subsurface storage, thus decreasing the FI. However, once the drain spacing is

A) Clay



B) Sand

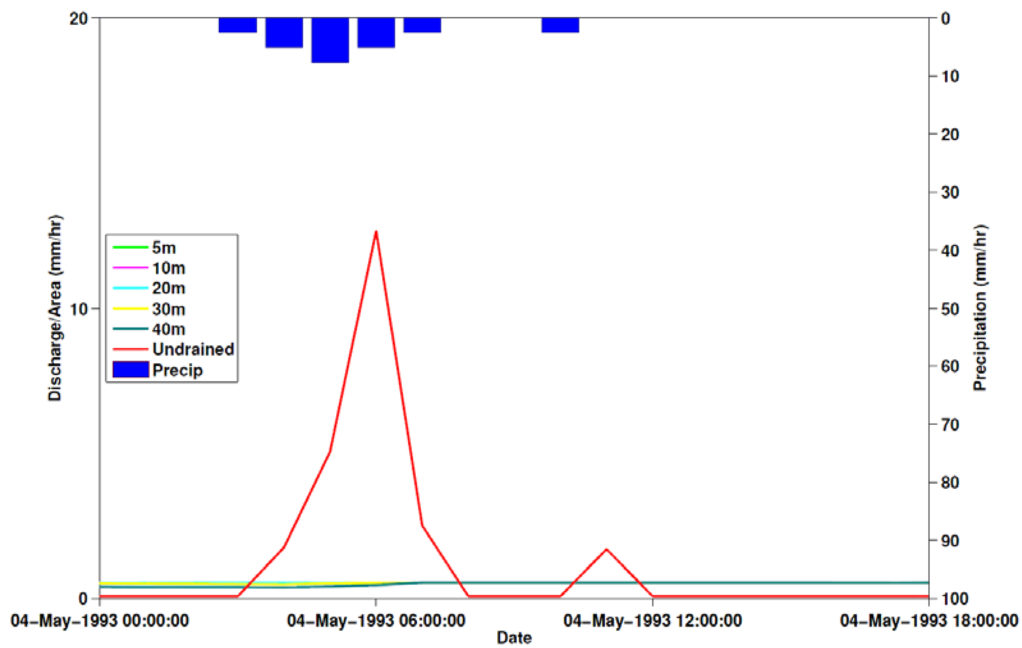


Figure 3-19 - Hydrographs with multiple tile spacings for two extreme soils in May 1993.

decreased beyond the optimal value, the closely spaced drains allow for fast subsurface routing, which leads to an increase in the FI. However, this does not mean that the peak flows are higher when the drainage is very close; rather, a larger volume of water is being moved each day than at other, larger spacings. The flashiness behavior in sand with an increase in drain spacing is different than in clay. The saddle shaped behavior is absent, and there appears to be a consistent increase in flashiness with a decrease in drain spacing. This is because the flow is primarily routed through the subsurface in sand, and adding closer drains merely speeds up the flow through that path.

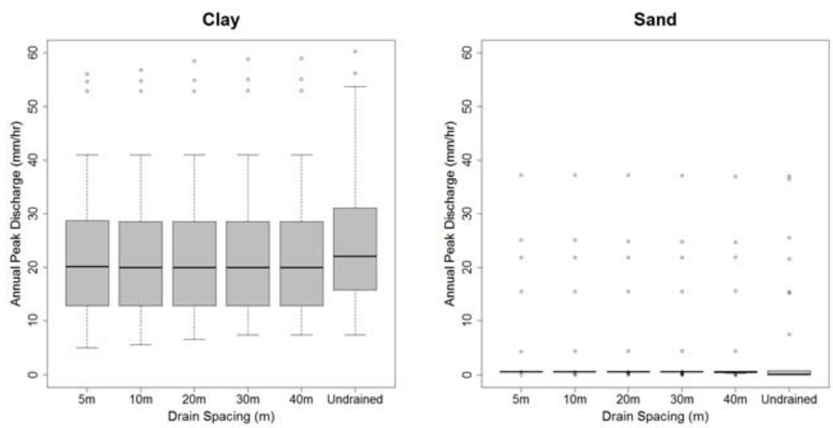


Figure 3-20 - Annual peak discharges at different drainage spacings for clay and sand.

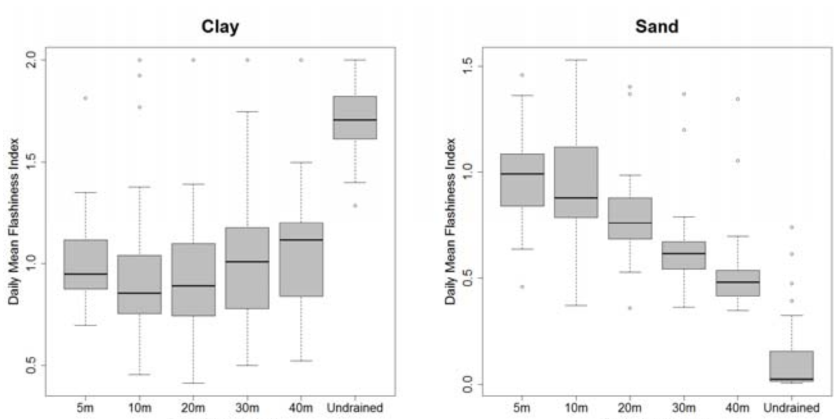


Figure 3-21 - Daily mean Flashiness Index for different drain spacings of clay and sand soils.

3.5 Field Scale Conclusions

Tile impacts on the hydrologic response involve a complex interplay among landscape, climatic, and anthropogenic controls at the field scale. The use of the deterministic field scale model DRAINMOD yielded useful results for the influence of each of these controls.

Soil type dictates the flow path that water will take once it lands on a particular field. For less permeable soils, the addition of tile drainage reduces the flashiness of the field by routing potential surface runoff through the subsurface, thereby decreasing the peaks of many events. For more permeable soils, the addition of tile can actually increase the flashiness of the system because the efficiency of the subsurface flow path, which is dominant before drainage, is increased. Additionally, increasing surface storage on the landscape tends to decrease the peaks significantly for less permeable soils regardless of drainage by promoting infiltration. This result is true for more permeable soils, but to a lesser extent because of the already large amount of infiltration. The increase in surface storage also seems to decrease flashiness in less permeable fields that are drained by reducing surface runoff, whereas in undrained, less permeable fields, the water infiltrates slowly and there are still surface runoff events. Surface storage has little impact on the FI of more permeable soils regardless of drainage.

These impacts, however, do not apply to all storm events; hence, the climatic influence on tile impacts. For very large storm events, the infiltration capacity or available subsurface storage is not sufficient to prevent large amounts of surface runoff. Therefore, in the case of certain size storms, tiling a field is of no consequence, which is an important conclusion when analyzing flooding events. This result disagrees with those found by Schwab and Fausey (1985) where larger storm events had greater reduction in runoff. However, the presence of either macropores or surface storage could explain the differences. Peaks could be reduced if macropores at the field site allowed for greater infiltration while not creating higher flow rates than surface runoff. Surface storage could also have a similar effect of allowing greater infiltration by retaining water on the surface longer. Macropores are not represented by DRAINMOD and surface storage is a very sensitive parameter, making differences between the analysis and the Schwab field study realistic. Additionally, the influence of rainfall is more dependent on individual storm events than on the cumulative amount of rain in a year, as indicated by the inconclusive results of separating the FI by rainfall years. In Iowa, for the 75th percentile of the average daily normal rainfall for the April through September, the addition of tile drainage significantly decreases the daily flow rates for much of the state because potential surface runoff is allowed to infiltrate. At the 25th percentile rainfall, most water is allowed to infiltrate in the drained and undrained fields, so the addition of tile significantly increases daily flow rates. The significance testing on the drained and undrained field results during different daily storm events also indicate that around 30 to 35 mm of daily rainfall is the threshold at which there is not a significant difference between a drained and undrained field. This threshold could indicate where either infiltration rate or subsurface storage capacity is exceeded and surface runoff is the dominant mechanism. However, is hard to make this conclusion due to the small number of samples for the larger storm events.

Finally, the spacing at which tiles are placed in a field will dictate the amount of subsurface storage in a field during a storm event and the amount of low flows after a storm event. The spacing of tiles has little to no effect on the annual peak flows since they appear to be dictated by climatic influences and surface runoff. However, in less permeable soils, there is a saddle behavior that indicates an optimal spacing. By decreasing drain spacing, infiltration is promoted and surface runoff is reduced. However, if the drain spacing is too narrow, the amount of water being routed through the subsurface and out of the tiles becomes larger on a daily scale and actually increases the FI more significantly than some larger spacings. In more permeable soils, the decrease in drainage spacing increases the FI universally because the majority of water that was being routed through the subsurface and closer tiles can move that water more efficiently.

These three controls rely entirely on one another and cannot be separated when determining the impact of tiles on the hydrograph response. These results, for the most part, agree with conclusions in the literature. Understanding these field scale mechanisms is essential to analyzing the catchment scale impacts in Chapter 4.

CHAPTER 4: CATCHMENT SCALE IMPACTS OF TILING ON HYDROLOGY

4.1 Introduction

The objective of this chapter is twofold: 1) to explore the impact of subsurface drainage on the hydrologic response at the catchment scale and 2) to understand the role of spatial placement of drainage on this response. At the field scale, useful qualitative conclusions have been posed previously and expanded on in Chapters 2 and 3 of this thesis, but little progress has been made in terms of utilizing this acknowledge or extrapolating it to the catchment scale. These field scale results are vital to understanding how tiles are altering the flow mechanisms of the landscape but are not directly applicable to the catchment scale at which flooding is analyzed. There are a couple of key reasons why scaling up field scale tile drainage results is problematic. The catchment scale hydrologic response is a function of the numerous field or hillslope contributions being routed through a channel network to the outlet. The magnitude of the field scale impacts of tile drainage on catchment hydrology is therefore going to be determined by the interaction of all field responses in the channel network. Since not all fields in the catchment are tile drained, the magnitude of tiling impacts at the catchment scale may be attenuated or “diluted” by the responses of the other fields. Also, the location or “distribution” of tiled fields in the watershed may determine the catchment response based on how flows from different fields synchronize at the outlet. Robinson and Rycroft (1999) refer to these two problems of scaling field results to the catchment scale as the “dilution” and “distribution” effects. There are, of course, other problems with scaling results, but these are the two main problems that this thesis addresses. Also, in this thesis, the catchment scale only refers to the 260 km^2 (~100 mi^2) scale, because that is the scale of the watershed that is being analyzed. These results cannot be assumed for larger watersheds due to greater complexities in the channel storage and routing at the larger scales.

To explore the two objectives, simplified catchment scale hydrologic model was created and used as a diagnostic tool on the Clear Creek Watershed (CCW) in Iowa and Johnson Counties, IA. The model performs a convolution with field scale DRAINMOD results and a simplified routing equation using MATLAB for a 30 year simulation period (1981-2010) in the CCW. Multiple scenarios were created and simulated to determine the magnitude of the impact of tiling at the catchment scale. The results are broken down into three main sections. First, the current conditions of the CCW are analyzed to verify whether the model gives reasonable results and to highlight the difference between field and catchment scale hydrographs. Second, the impacts of draining the entire watershed and removing all drainage are analyzed to show how subsurface drainage affects the hydrograph response. Third, spatially-varied drainage scenarios are analyzed to explain how the location of tiling in a catchment may have an impact on the hydrograph response. Both single-storm hydrograph analyses and integrated time metrics are included in each section. Overall, this portion of the thesis is a first order analysis that provides a diagnostic tool for determining whether there is a fundamental impact of tiling at the catchment scale.

4.2 Methodology

4.2.1 Site Description and Data

The Clear Creek Watershed (CCW), located in northern Iowa and Johnson Counties, was selected for this study. The area (267 km^2) is an intensively farmed region of Iowa with just over 50% of the watershed being used for agriculture, and the rest of the area is being primarily used as ungrazed grassland (Iowa Geologic and Water Survey). The location and land use map for the CCW are shown below in **Figure 4-1**. The land use data are from the Iowa DNR for 2002. The watershed consists of mainly silt loam and silty clay loam, according to the USDA textural classes obtained from the USDA-NRCS SSURGO database. The CCW is located in the Loess Ridges/Glacial Till region of Iowa containing Colo-Ely, Ladoga, and Otley soils (among others), which require some drainage for optimal agricultural performance, according to the Iowa Drainage Guide (USDA - NRCS; Iowa State University Extension and Outreach, 2012). The slopes in the watershed are generally higher than 5%, which may involve non-parallel or more randomly-spaced drainage lines. The tile configuration in DRAINMOD is parallel, so the actual tiles in the CCW may not be as well represented. However, considering the poorly drained soils, the lack of an accurate map of tile locations in the area, and the popularity of tiling in the farming community, the assumption using DRAINMOD to represent extensive tiling in the CCW is reasonable.

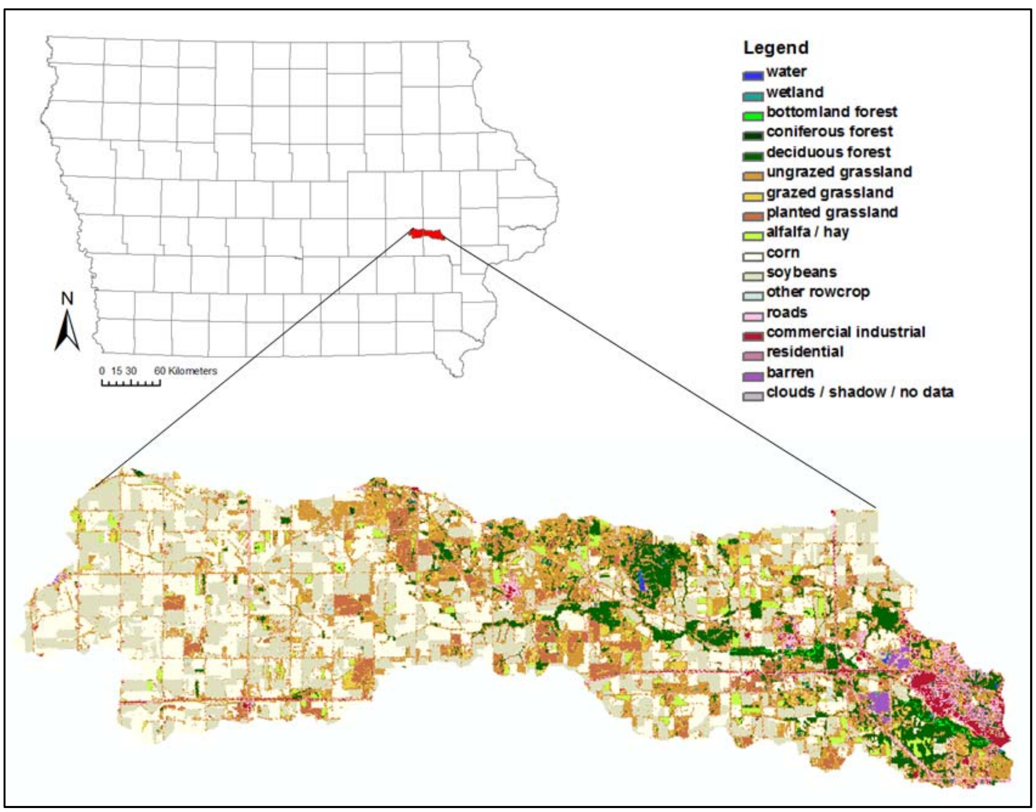


Figure 4-1 - Clear Creek Watershed Land Use and Location Map.

The CCW was selected due to the large amount of available data from the Iowa Geologic and Water Survey (IGWS) and the Iowa DNR. Land use, topographic, and stream network data for the CCW were obtained from the NRGIS Library and from Professor Ricardo Mantilla at The University of Iowa. In particular, Professor Mantilla supplied the individual hillslope data, which were delineated using the GIS program, CUENCAS. The hillslopes are defined as the areas contributing water directly into a stream link and are derived in CUENCAS using the concavity of the land. The 6,359 delineated hillslopes are shown below in **Figure 4-2**. Soil and geologic data were obtained from the USDA-NRCS Soil Survey Geographic Database (SSURGO). All of the data were analyzed using ArcGIS in order to create inputs and scenarios for the simplified hydrologic model. Below, in **Figure 4-3**, is a Google Earth map of the Clear Creek stream network. It is important to note that the southeast tip of the CCW is not included in this analysis, so the actual area of the analysis is closer to 253 km^2 rather than to 267 km^2. The reasoning behind the exclusion is that the watershed was delineated from the USGS Clear Creek stream gauge (USGS #05454300).

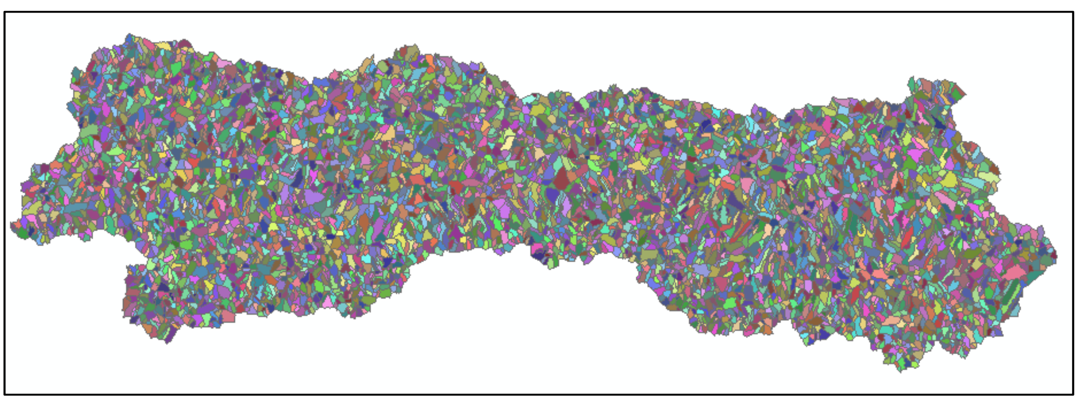


Figure 4-2 - The individual hillslopes of the Clear Creek Watershed Delineated by CUENCAS.

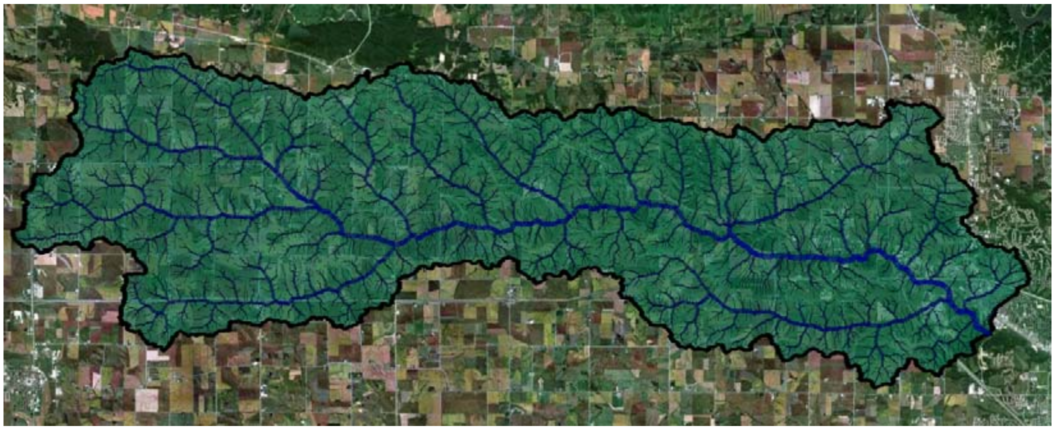


Figure 4-3 - Google Earth image of the Clear Creek Watershed stream network.

4.2.2 Simplified Catchment Scale Hydrologic Model

4.2.2.1 Routing Equation

As previously mentioned, the model created is a combination of field scale DRAINMOD outputs and a simplified routing equation. An extensive description of DRAINMOD is given in Section 3.2 and will not be covered further in this section. The DRAINMOD outputs explain only what happens at one hillslope, so there needs to be a way to route the flows from the 6,359 separate hillslopes in the CCW to the outlet. An analytic expression for a scale dependent geomorphologic instantaneous unit hydrograph (GIUH) was used in the model. This expression was developed by Mantilla, Navarro, and Ramirez based on the previous work of Gupta and Waymire and Manbde et al. (Mantilla, Navarro, & Ramirez, In Revision 2013). The analytic expression is a solution to the link-based water transport equation:

$$\frac{dq_i(t)}{dt} = K\big(q_i(t)\big)\big[R_i(t) + q_{i_0}(t) + q_{i_1}(t) - q_i(t)\big] \tag{4.1}$$

where i is any stream link, i_0 and i_1 are upstream tributaries, $q_i(t)$ is the flow at any time for link i, $K\big(q_i(t)\big)$ is a non-linear function that represents the inverse of residence time of water in a channel link, $R_i(t)$ is the discharge from the hillslopes of the link, and

$q_{i_0}(t)$ and $q_{i_1}(t)$ are incoming discharges from the uphill tributaries. There are a couple of simplifying assumptions that allow for an analytic solution to this equation. The assumption of a constant velocity, v, and an average link length, l, are assumed, which makes $K(q_i(t)) = v/l$. This implies that discharge is a linear function of storage:

$$q_i(t) = \left({}^{v}/_{l}\right)S_i(t). \tag{4.2}$$

The solution to **Equation 4.1** and the routing equation used in the simplified catchment scale model is as follows:

$$q_i(t) = e^{-\frac{v}{l}t} \sum_j \frac{q_j(0)}{(d_{i,j}-1)!} \left(\frac{v}{l}t\right)^{d_{i,j}-1} \tag{4.3}$$

where $d_{i,j}$ is the topologic distance from the outlet to a hillslope, and $q_j(0)$ is the instantaneous discharge contributed from a hillslope at a particular time. Topology is used in the equation because of the simplifying assumption of an average link length. **Equation 4.3** assumes that the CCW is a linear system, meaning that flows at the outlet can be calculated by the summation of all the hillslope hydrographs upstream after they are adjusted or stretched to account for storage in the river network. In this case, the hourly DRAINMOD output is considered $S_j(t)$, so $q_j(0)$ is equal to *v/l* times the DRAINMOD output. The constant velocity (v) is assumed to be 0.8 m/s based on the maximum distance to the outlet and personal correspondence with Professor Mantilla, in which he confirmed that the time of concentration for the CCW is around 24 hours. The constant link length (l) value is the average of the link lengths that were delineated for the CCW. This routing equation simplifies the natural world significantly but is useful for creating this diagnostic tool.

4.2.2.2 DRAINMOD Simulations

Hourly DRAINMOD simulations were applied to the hillslopes and routed to the outlet. However, running a DRAINMOD simulation for each hillslope would have been inefficient and unrealistic for this analysis. Therefore, the 6,359 hillslopes were binned into an appropriate number of DRAINMOD simulations based on USDA soil textural classes. The soil textural classes are not completely representative of the natural heterogeneity at each hillslope in the CCW, but there are data readily available on their geographical locations and soil hydraulic parameters, which makes modeling feasible for this first order analysis. Each hillslope was assigned a soil textural class by using the Identity tool in Arcmap 10 and the ArcGIS tool SoilDataViewer 6.0, which maps SSURGO data automatically. Once the appropriate soil textures were loaded from SoilDataViewer 6.0 into the hillslope attribute table, they were sorted and ranked by area to find the most likely majority soil type of each hillslope. There is some potential for error using this method, but after double-checking the results with a soil map generated by the SSURGO data, the results seemed reasonable. **Figure 4-4** shows the soil textural classes of all of the hillslopes in the CCW. Those hillslopes that were unassigned by SSURGO had a random soil type applied to them from the six main types seen in the CCW. Since there are only six soil textures in the CCW, according to the SSURGO data, the decision was made that there should be a total of 12 DRAINMOD simulations run: 6 with tile drainage and 6 without for each soil type.

The DRAINMOD simulations were run using 30 years of hourly rainfall data and daily temperature data from the Iowa City weather station (COOP #134101), which were obtained from the NCDC website (NOAA - National Climatic Data Center). The soil hydraulic properties input into DRAINMOD were convenient since they are available for the main USDA soil textural classes. The hydraulic soil properties (often referred to as Van Genuchten parameters) for each textural class obtained using the pedotransfer

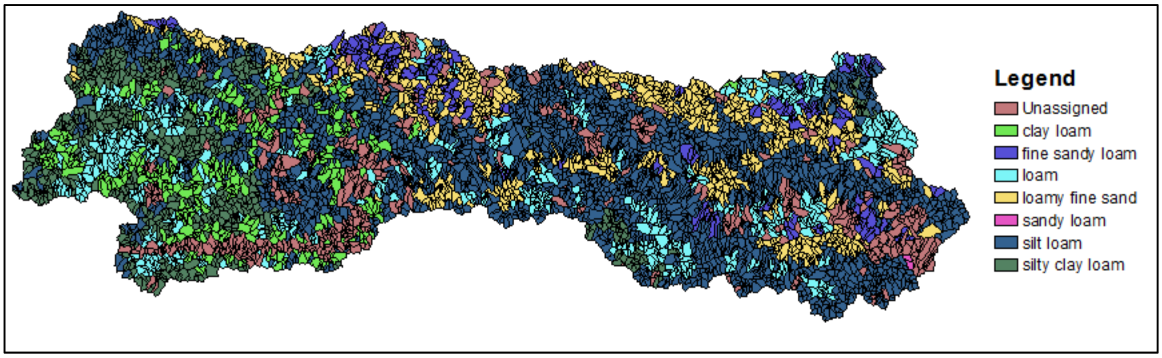


Figure 4-4 - The USDA soil textural classes assigned to each hillslope of the Clear Creek Watershed.

function ROSETTA are located in **Table 3-1** because they were used in the field scale analysis as well (USDA - Agricultural Research Services, 2005). The six drained scenarios had a tile spacing of 20 m (~66 ft), based on typical values for the watershed soils from the Iowa Drainage Guide (Iowa State University Extension and Outreach, 2012). The undrained scenarios were identical to the drained scenarios, but the drains were effectively turned off by setting the drainage coefficient equal to zero. Realistically, the ET and surface storage of these unfarmed hillslopes would be different from the drained agricultural fields. However, some sensitivity analysis was performed with ET values for the simulation period in DRAINMOD, and the effect on outflow (surface runoff only) was minimal since the crops could not typically be planted on time or at all each year without tile drainage. The surface storage of the undrained fields may be greater than that of the agricultural fields, and assuming similar surface storage could cause an overestimation of surface runoff from the undrained fields. The impacts of surface storage at the field scale are examined in Section 3.4.1.2, and the results on undrained fields showed that peaks could be reduced with increasing surface storage. However, given that the impact was more drastic for drained fields and that there is available data to realistically adjust the surface storage parameter, it was left the same as the drained scenario. The outputs from DRAINMOD used in the catchment scale hydrologic model are the water loss output plus the lateral seepage value used in the field scale analysis of this thesis and described in Section 3.3.3. The DRAINMOD inputs for one drained scenario are included in **Appendix A**.

4.2.2.3 Algorithm for the Simplified Catchment Scale Hydrologic Model

MATLAB was used to create the simplified catchment scale hydrologic model. Essentially, the script created in MATLAB loads in the hourly outputs from DRAINMOD and the soil type, topologic distance to the outlet, and the area of each hillslope in the CCW based on the scenario. The script then executes a convolution with **Equation 4.3** to obtain the outlet hydrograph. **Equation 4.3** creates one outlet hydrograph in time for all hillslope flow inputs at one time step. Therefore, each time there is another input from the hillslopes, a new hydrograph in time is created and the sum of all the created hydrographs is the overall outlet hydrograph, which is a convolution. In this case, the flow input is the water loss plus lateral seepage from DRAINMOD for each hillslope. One way to code this process is to perform a convolution using all 6,359 hillslopes and their specific discharges for the entire 30 years of time series, which would be extremely slow and computationally intensive in MATLAB. However, an algebraic manipulation of the routing equation allows for great computational simplification and efficient coding.

The assumption was made that the hillslopes are separated into groups by drainage type and USDA soil texture. For each group of hillslopes, there is one DRAINMOD output, which would need to be multiplied by the respective area of the hillslope (A_j) and v/l to get the $q_j(0)$ value, since DRAINMOD outputs are area normalized. However, by removing the $q_j(0)/A_j$ from the summation term in **Equation 4.3** and multiplying the $e^{-\frac{v}{l}t}$ term into the summation, a constant unit response can be calculated for each hillslope group based on the topologic and area data of all hillslopes in the group. In order to ease computations, the time chosen for the unit response is 40 hours, since it is assumed that most of the water from a runoff event reached the outlet by 40 hours in the CCW. This 40 hour time interval in **Equation 4.3** refers to the time for which each hydrograph from a flow input is calculated. Then, a convolution is performed for each hillslope group between the area normalized DRAINMOD output and the unit response constant in order to obtain the outlet hydrograph of each hillslope group. These outlet hydrographs are summed in order to obtain the total outlet hydrograph of the time series. The simplification is presented in **Equation 4.4**:

$$q_i(t) = \frac{q_j(0)}{A_j} \sum_j \frac{A_j e^{-\frac{v}{l}t}}{(d_{i,j}-1)!} \left(\frac{v}{l} t\right)^{d_{i,j}-1} \tag{4.4}$$

where $q_j(0)/A_j$ is the DRAINMOD hourly output for the hillslope group, and the summation term is the unit response constant for the hillslope group. A process diagram of the MATLAB code is shown below in **Figure 4-5**. The MATLAB code is located in **Appendix C** with full annotations.

The hydrologic model created in MATLAB has many underlying simplifying assumptions. Assuming that an entire watershed can be separated into 12 scenarios removes much of the heterogeneity that makes large scale hydrology so complex. Additionally, the spatial variability of rainfall is also removed because each hillslope receives the exact same rainfall input, which is implied by a DRAINMOD simulation being applied to each hillslope. The DRAINMOD inputs at the hillslope scale are also approximations that are inherent to the model and do not fully capture many of the complexities of undrained field sites and developed areas. Finally, assuming that CCW is a linear system and can be described by a constant velocity and average link length removes complexity from the river network and routing. However, with all the caveats, this model is still a useful diagnostic tool that represents the complexity of the natural system well enough to determine fundamental behaviors about the impacts of tiling at the catchment scale through the analysis of different design scenarios. DRAINMOD has been proven effective over the previous 30 years of research, and Professor Mantilla has found through his previous years of work that CCW is well represented with the assumption of linearity. Furthermore, this section provides an intuitive framework for other researchers to utilize in catchment scale analysis.

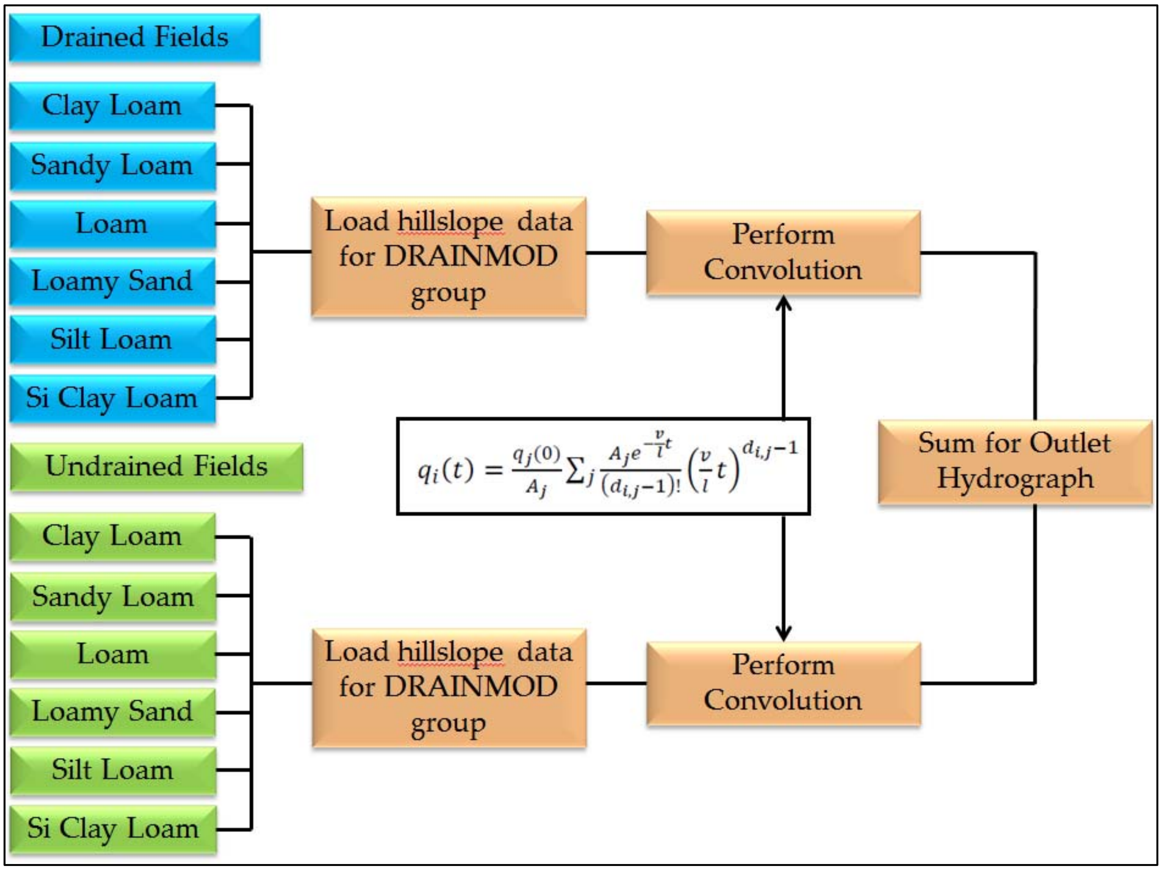


Figure 4-5 - Schematic of how the simplified catchment scale hydrologic model runs in MATLAB.

4.2.3 Design Scenarios

The overriding purpose of creating this model and doing this analysis is to use the field scale results to answer questions about the catchment scale impacts of tile drainage. In order to achieve this, seven design scenarios were created. Below are the descriptions of the scenarios, with their names that are used in the results in parentheses. The first three scenarios were developed to explain how the catchment scale hydrographs differ from the field scale hydrographs and to determine the overall impact of the addition of tile drainage on a watershed. The first scenario (Original) assumes that all of the hillslopes with row crop agriculture (according to the NRGIS Library 2002 land use map) are drained, while all other fields are undrained. The second and third scenarios were selected to visualize the end-member situations. The second scenario (All Drained) assumes that all fields are tile-drained, and the third scenario (All Undrained) assumes that all fields are undrained. These three scenarios' results are presented in Section 4.3.1 to 4.3.3. The next two scenarios were created as a test to determine whether the position of tiled fields in the watershed has an impact on the outlet flows. The fourth scenario (Far Drainage) assumes that the only fields drained are all of the drained hillslopes from the Original Drainage scenario above a topologic distance of 304 links from the outlet. The fifth scenario (Near Drainage) assumes that the only fields drained are all of the drained hillslopes from the Original Drainage scenario with a topologic distance less than 220 links from the outlet. For comparison's sake, the Far Drainage and Near Drainage scenarios were chosen so that the total area of tiled fields in each scenario is about 20% of the total catchment area. The last two scenarios were selected to determine whether the position of tiled fields in relation to each other (clustering) impacts the outlet hydrograph. Additionally, the last two scenarios were run assuming that the entire watershed consisted of silt loam in order to remove the impacts of different soil types. Silt loam was selected since it is the most prevalent soil in the CCW. The sixth scenario (Clustered Far Drainage) assumed that all fields with a topologic distance greater than 290 links from the outlet are drained. The seventh scenario (Clustered Near Drainage) assumed that all fields with a topologic distance of less than 164 links from the outlet are drained. These selected drained hillslopes correspond to 30% of the catchment area (76.5 km^2). The last four scenarios' results are covered in Section 4.3.4. All scenarios, excluding All Drained and All Undrained, are shown below in **Figure 4-6**.

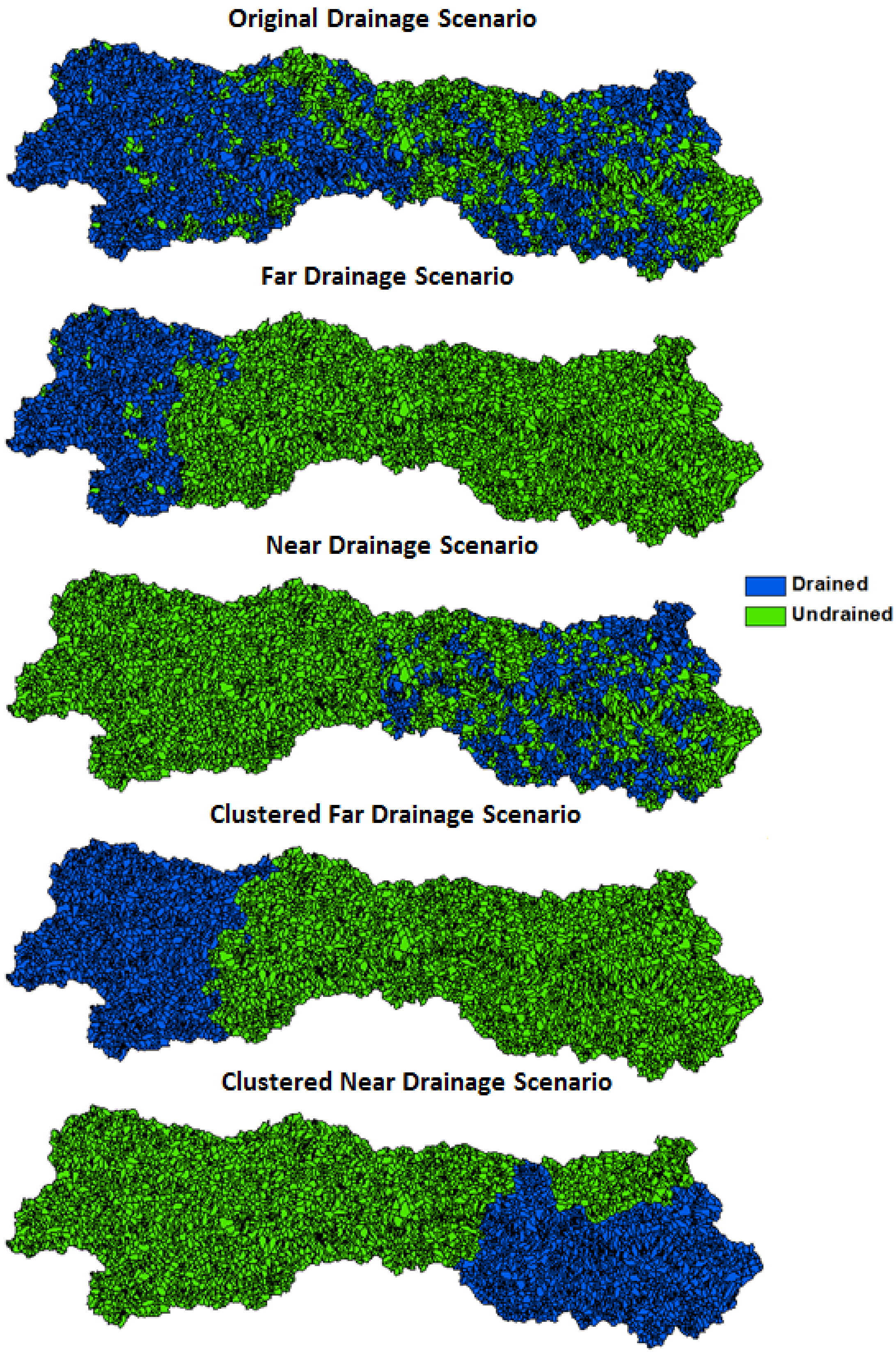


Figure 4-6 - Five key drainage scenarios for analysis of the Clear Creek Watershed.

4.3 Results and Discussion

The simulation results were analyzed to determine the difference between field scale and catchment scale hydrographs, the impact of subsurface drainage on the hydrographs at the catchment scale, and the importance of the spatial location of drained fields in the watershed. There are 30 years of simulation results overall, but for the hydrograph analysis only events from the summer of 1993 were selected. The year 1993 in Iowa was a very wet year with much flooding, so it is a good year for analyzing hydrologic impacts. Additionally, other years were examined to ensure that the conclusions are not just unique to 1993 events, but they are not shown in this chapter. Further, The 30-year time series of data was used to explore flow regime shifts due to tiling using metrics such as the Flashiness Index, and the Flow Duration Curve.

4.3.1 Model Comparison with USGS Stream Data

The purpose of this model is not to calibrate and validate to Clear Creek gauge data but, rather, to use it as a diagnostic tool to understand some fundamental concepts behind tiling impacts at the watershed scale. However, a comparison to USGS stream gauge data is necessary to ensure that the model's outputs are reasonable in terms of event magnitudes and timing. The USGS Stream Gauge (#05454300) for Clear Creek near Coralville, Iowa was compared to the Original Drainage scenario results (United States Geological Survey). The model captures the duration and magnitude of larger events better than it captures them for smaller events. In some cases, the model captures large event hydrograph behavior very well. **Figure 4-7** is a hydrograph comparison of an early July 1993 event in which the large hydrographs' shape and magnitude are represented well by the model. The smaller events seem more poorly represented by the model, but the comparison ensured that the use of the model as a diagnostic tool would be worthwhile overall.

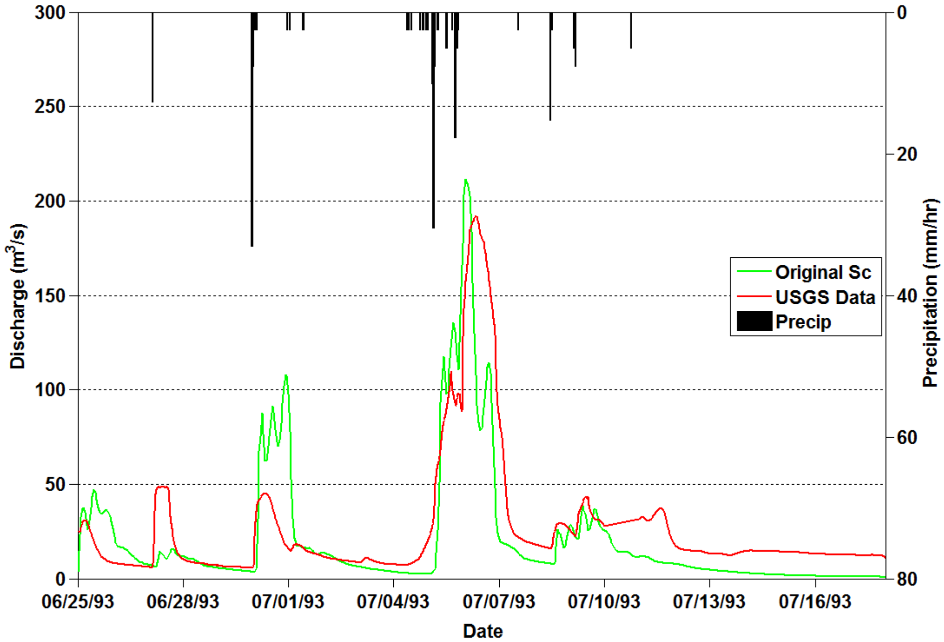


Figure 4-7 - A comparison of model outputs with USGS Stream Gauge for Clear Creek near Coralville, IA for an early June 1993 event.

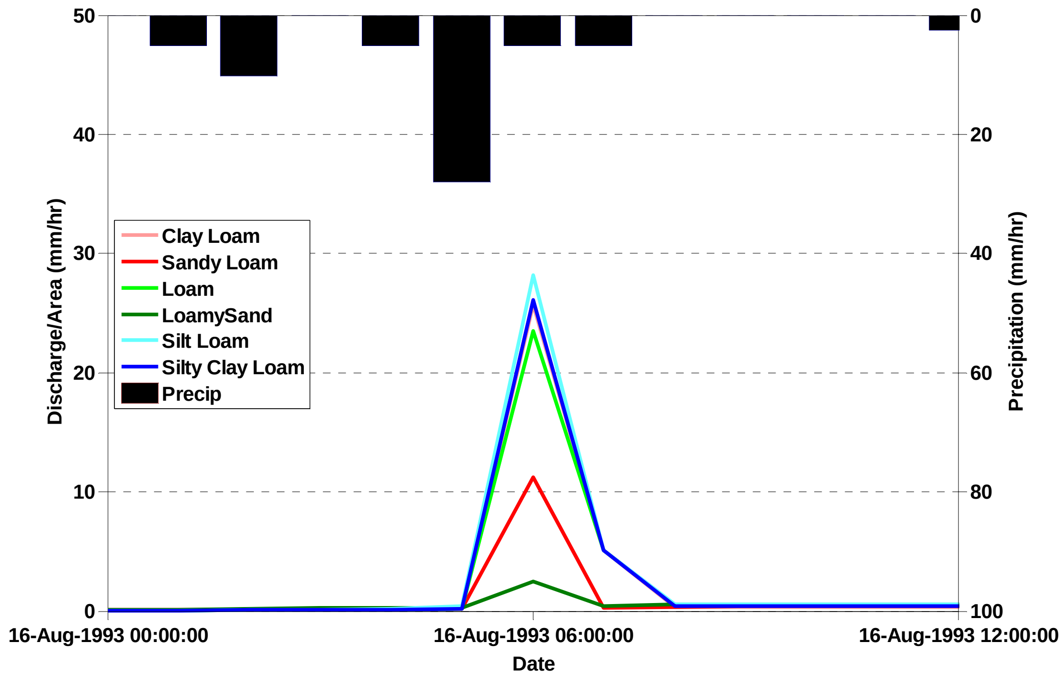
4.3.2 Comparing Field Scale and Catchment Scale Hydrographs

The main reasons that field scale results cannot be scaled up to the catchment level is because of the dilution and distribution effects mentioned by Robinson and Rycroft (1999). The hydrograph leaving a field or hillslope combines with hydrographs from other hillslopes and is routed through the river network where there is an additional storage and interaction, which changes the timing of the hydrograph reaching the outlet. The field scale hydrograph shape is essentially transformed to an outlet response. To illustrate this point, **Figure 4-8** displays one event in August 1993. **Figure 4-8 A and B** are the field scale hydrographs of each soil type for drained and undrained fields, respectively. **Figure 4-8 C** is the catchment scale hydrograph for the storm event, with a color separation that illustrates the contributions from drained and undrained fields.

The difference between the drained and undrained field scale plots is apparent. The drained fields have lower peaks for the large rainfall event, and there are differences between the peaks of the different soil types. On the contrary, the undrained fields have a higher peak and primarily one shape for all soils. Additionally, the drained fields do not record an event during the first smaller rainfall event on August 16th,which implies that water is being stored in the soil and released slowly, while there is a runoff event from the undrained fields. These differences are a function of the drained fields having available subsurface storage and higher infiltration rates for the incoming precipitation. Additionally, since tiling is a slower flowpath, its signal is very gradual in the hydrograph, which makes it nearly insignificant in large events. The tile flow itself is not important, but the reduction of the fast surface flow in the drained fields' hydrographs is significant. On the drained field plot, the majority of apparent flow is surface runoff, but it is much less surface runoff than the undrained fields' hydrographs because of the amount of water that is allowed to infiltrate.

The differences between the field hydrographs and the catchment hydrograph are very significant. First, the catchment hydrograph lasts for nearly a day, whereas the field hydrograph lasts for a couple of hours. Second, there are multiple peaks occurring in the catchment hydrograph, which is a function of the river network and the arrival times of flows from different distances. The width function of the river network plays a key role in the hydrograph's shape and will be discussed later in Section 4.3.4. Third, the contributions of drained and undrained field hydrographs are dependent on their location in the watershed. In Error! Reference source not found. **C**, the undrained fields contribute slightly more on August 16th, but the contributions are mainly from the drained fields on August 17th. This makes sense when looking at the Original Drainage scenario in **Figure 4-6**, where the headwaters are highly drained and, thus, will take the longest to reach the outlet. The dilution and distribution effect make it difficult to understand how these field hydrographs are impacting the overall catchment hydrograph and prove the need for a diagnostic tool.

A) Drained Field Hydrograph



B) Undrained Field Hydrograph

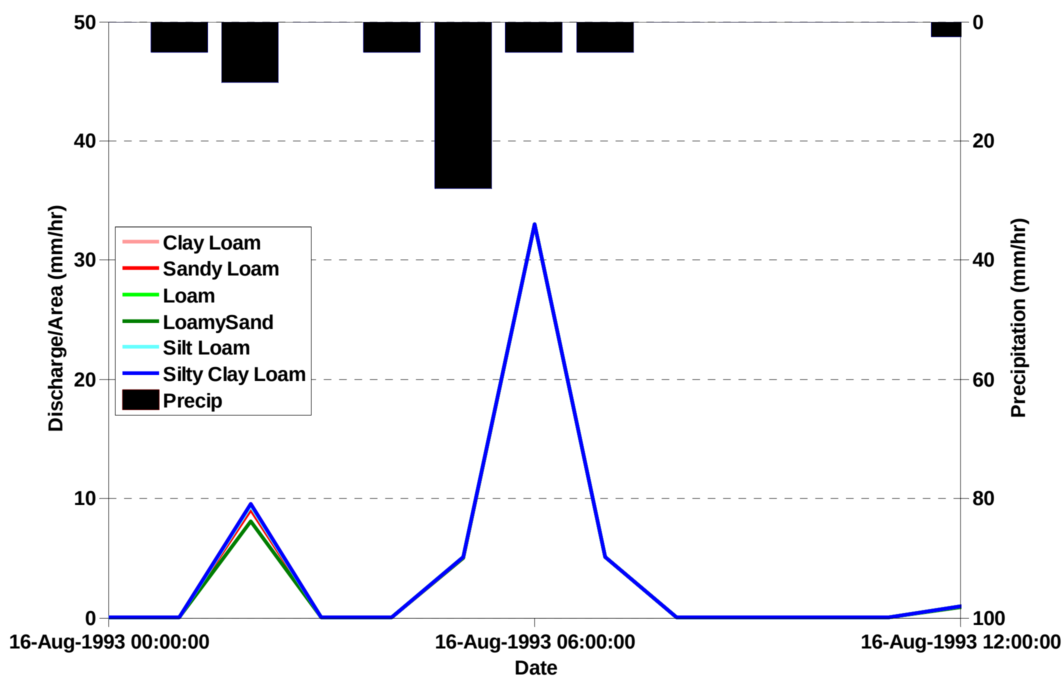


Figure 4-8 - Comparison of field and catchment-scale (Original Scenario) hydrographs for a large August 1993 event.

C) Catchment Hydrograph

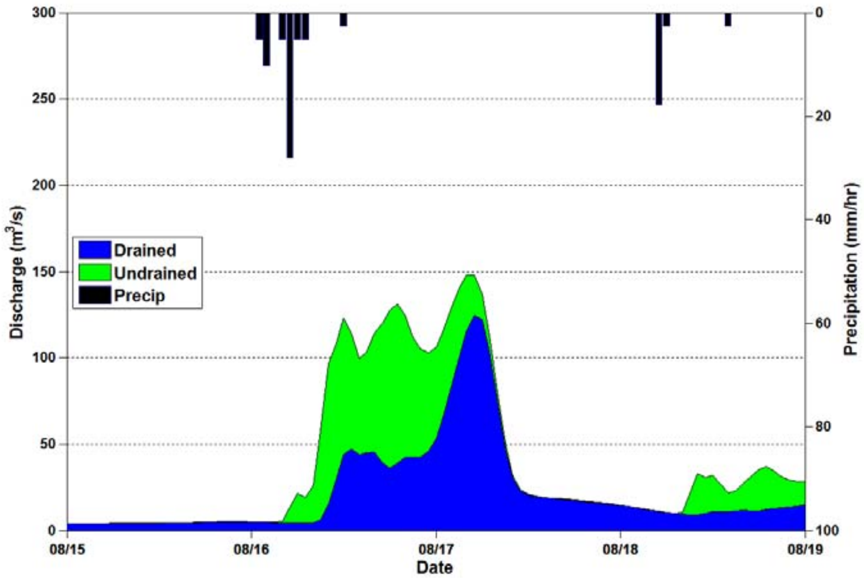


Figure 4-8 continued

4.3.3 The Role of Subsurface Drainage on the Hydrograph Response at the Catchment Scale

4.3.3.1 Analysis of Event Hydrographs (Scenarios 1-3)

The purpose of this section is to determine how tile drained fields impact the catchment scale hydrograph. In order to do this, the Original Drainage scenario is compared to the two end-member scenarios: All Drained and All Undrained. Two different rainfall-runoff events from August 1993, shown in **Figure 4-9**, were selected for this section because they display two different behaviors. The first event, which transpired on August 10th, shows very little difference among the three scenarios, whereas the August 17th event has three separate hydrographs with similar shapes but different magnitudes.

The later August event is the best event to analyze when determining the impact of tiling on the catchment hydrograph. The event hydrographs for the three scenarios are shown in **Figure 4-10**. According to the hydrographs, adding tile drainage reduces the peak flows at the outlet. The overall water leaving the outlet is very close, since both the

Original and All Drained Scenarios have larger baseflows following the peak, which are caused by water being released slowly by drain tiles. Looking at the soil component hydrographs and the field scale hydrographs help to explain why peaks are decreased by adding tile drainage to the watershed.

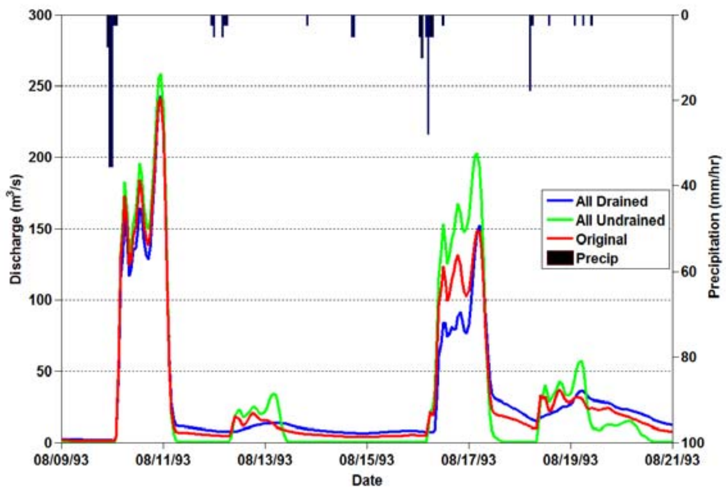


Figure 4-9 - All Drained, All Undrained, and Original Scenario hydrographs in August 1993 that show two distinct behaviors.

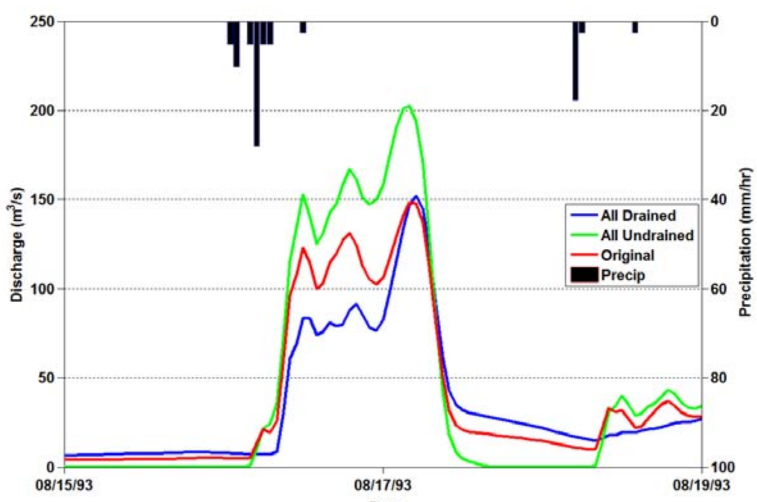
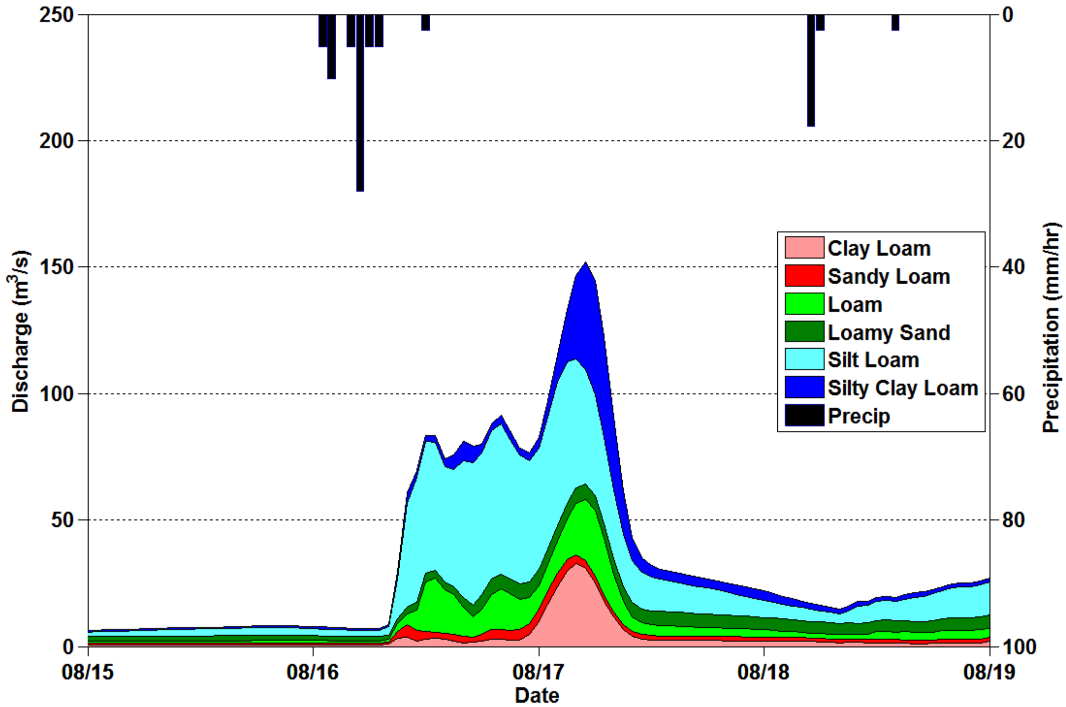


Figure 4-10 - August 1993 hydrograph of the All Drained, All Undrained, and Original Scenario.

The soil component hydrographs display the portion of the outlet hydrograph that is attributable to the contribution of fields of that particular soil type. **Figure 4-11** displays these for the three scenarios of interest and reveals the mechanism that causes lower peaks that result from tile drainage in the watershed. The magnitude of the soil component hydrographs for the All Undrained Scenario is larger than the Original and All Drained scenarios. The shapes are very similar, but the magnitudes differ. This can be explained further by the field scale hydrographs shown in **Figure 4-8 A and B** for this same event. There is a smaller field scale hydrograph coming from the drained fields than from the undrained fields. This is because there is subsurface storage created by the tiles, which allows more water to infiltrate and exit the field via tile drainage thereby creating a more gradual hydrograph than the undrained fields. Therefore, the more drained fields in the watershed, the less the signal of the drained fields is diluted at the catchment scale. In other words, adding drainage reduces the amount of fast surface flow entering the channel network and consequently reduces the overall catchment hydrograph because the larger flows cannot combine with one another.

This conclusion that tiling reduces peaks at the catchment scale is not universal for all rainfall events, as indicated by the fact that the hydrographs of the August 10th event in **Figure 4-9** are so close together. The soil component and field hydrographs are not necessary to explain the mechanism behind this behavior. Essentially, for very large storm events, the rainfall is either so intense or so great in volume that surface runoff is the dominant mechanism due to either infiltration excess or subsurface storage excess runoff. Therefore, all fields and, typically, all the different soil types have a similar hydrograph because the flow mechanism is the same during these large events regardless of tile drainage. This results in nearly identical catchment scale hydrographs. Therefore, the conclusion can also be posited that for some large storm events that would cause flooding, tiling essentially has no impact and the river network routing the flow dictates the outlet hydrograph.

A) All Drained Scenario



B) Original Scenario

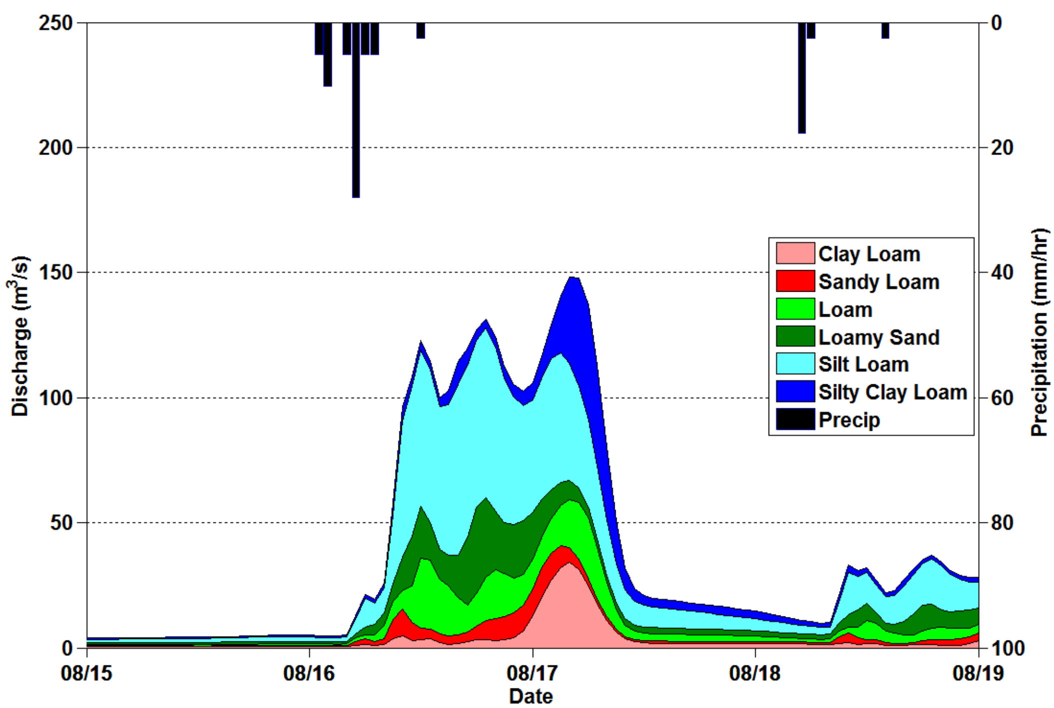


Figure 4-11 - August 1993 Soil Component Hydrographs for the Original and two end-member scenarios.

C) All Undrained

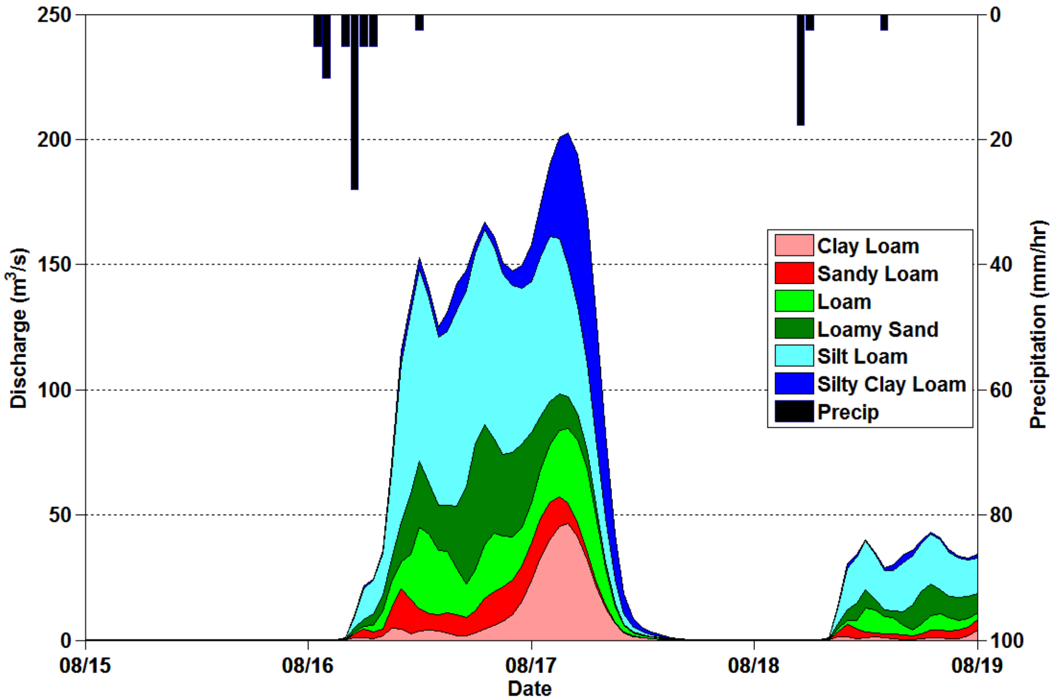


Figure 4-11 continued

<u>4.3.3.2 Analysis of Flow Regime Shifts from Tiling</u>

The hydrograph analysis is important and uncovers the mechanisms that cause the response of the outlet hydrograph. However, some metrics are more useful at describing the overall hydrograph behavior of a long time series of data. There are 30 years of hourly results from the simulations that were run with the simplified hydrologic model. Three metrics were selected to analyze the overall impact of tile drainage on hydrograph response: 1) Annual Hourly Peak Flows, 2) the Richard-Baker Flashiness Index (FI), and 3) Flow Duration Curves (FDC).

The annual hourly peak flows exhibit the largest hourly flow of each year from the simulation time period of 1981-2010, as shown in **Figure 4-12**. In about 2/3 of the years (19 years), the All Undrained has a significantly larger peak flow than the other two scenarios. This indicates that the tiled fields in the All Drained and Original Scenario are able to reduce the largest peak flow of those years by routing potential surface runoff through the slower subsurface flow path. This leaves nearly 1/3 of the years of simulated results being invariant to the impacts of tiling for the largest storm event. This makes sense considering the hydrograph analysis in the previous section, where the August 10th event's hydrographs were determined to be invariant. The largest flows of those 11 years are probably due to very intense and large cumulative rainfall events, where there is a large amount of surface runoff regardless of soil type and drainage. These results consider only 30 total events, so the FI and FDCs are analyzed to get an idea of the impact on the entire flow regime.

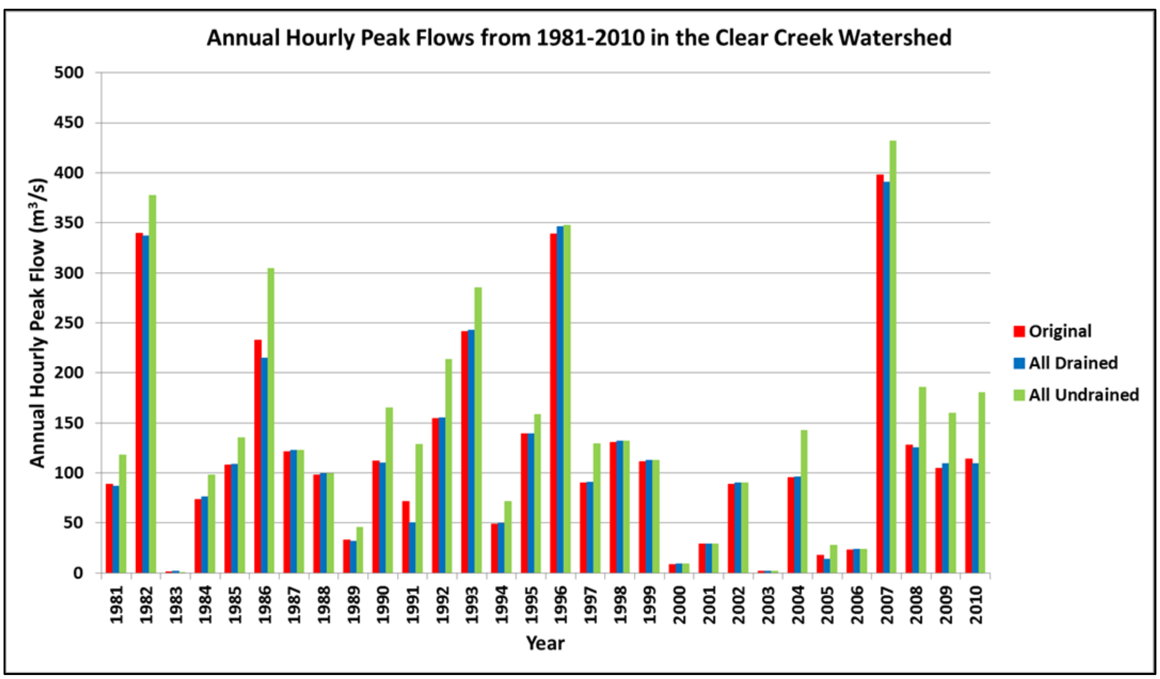


Figure 4-12 - Annual Hourly Peak Flow for the simulated hydrologic response of Clear Creek Watershed from 1981-2010.

The FI, shown below in **Figure 4-13,** offers a good indication of how quickly the system responds to a rainfall event. The results are as expected, with the All Drained being the least flashy and the All Undrained being the flashiest. The results indicate that for most runoff events, the All Undrained scenario has a larger proportion of flow through the surface pathway, which leads to flashier hydrographs, whereas the increased proportions of subsurface flow in the Original and All Drained scenarios decreases the hydrograph peaks. However, during small events, drained fields could cause larger hydrographs since the undrained fields may not have any surface runoff and only very little lateral seepage. Those events are typically less significant, however, and do not have much impact on the indicator.

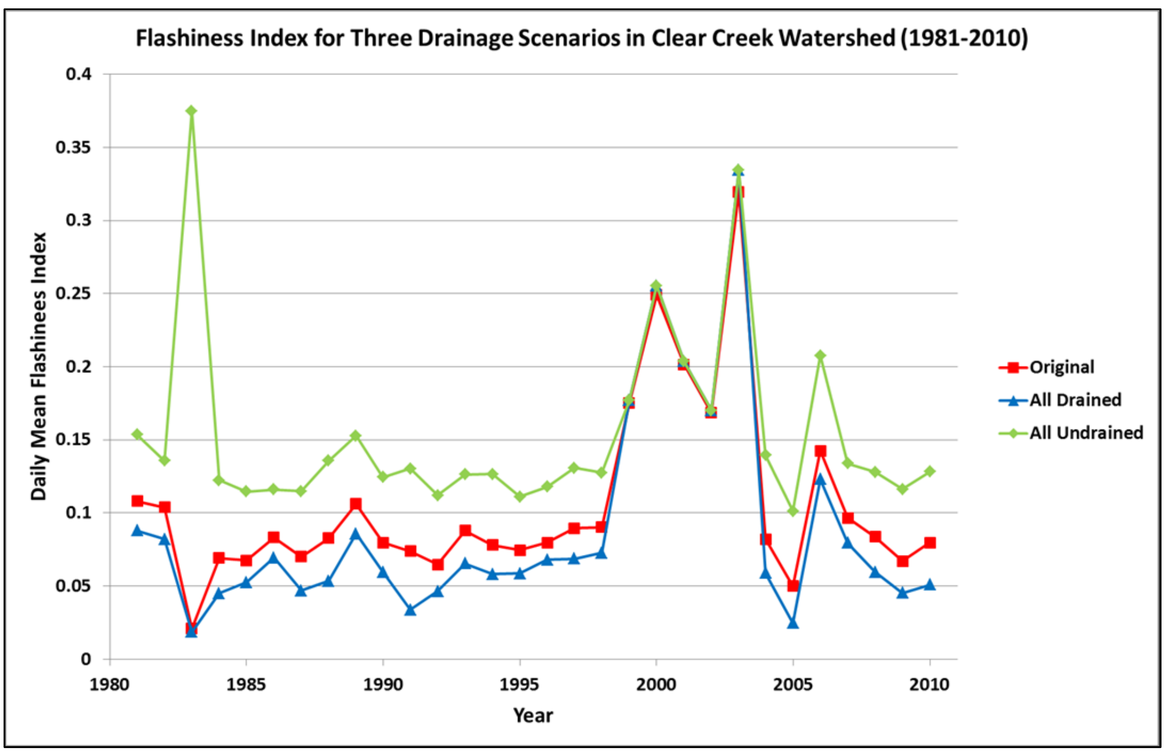


Figure 4-13 - Richard-Baker Flashiness Index for the Clear Creek Watershed from 1981-2010.

The Flow Duration Curves (FDCs) provide another indicator of the impacts of tile drained fields on the flow regime. The FDCs of the three scenarios for the exceedance probability of less than 10% (100 year event) are shown below in **Figure 4-14** because those are the flows deemed most significant. There are three separate conclusions that can be drawn from the FDCs. First, there is an inflection point that occurs at around 2.5% exceedance probability. At this point, the order of the largest flow for the exceedance probability reverses from All Drained, Original, and All Undrained, respectively. This means for exceedance probabilities that are greater than 2.5%, the All Drained scenario has the greatest flow rate, while the All Undrained scenario has the smallest flow rate, and the Original scenario is in the middle. This makes physical sense, since these smaller flow events are caused by subsurface contributions to the stream network, and tile drainage will deliver higher flow rates than the lateral seepage that is coming from the undrained fields. Second, after the inflection point, the All Undrained scenario is the highest because, during these flow events, surface runoff is dominant and the largest peaks will come from the inundated undrained fields. The Original and All Drained scenarios have tiled fields in the watershed, which reduces the amount of surface runoff and converts it to slower subsurface flow. Third, during very large events (< 0.04%), there is essentially no difference in the FDCs. The explanation for this is exactly the same as the explanation for the identical hydrographs during the August 10th event in Section 4.3.3.1. At a certain rainfall intensity or cumulative volume, tile drainage has no impact since all the rainfall is shedding from the surface due to infiltration excess runoff, at which point the channel network dictates the peaks.

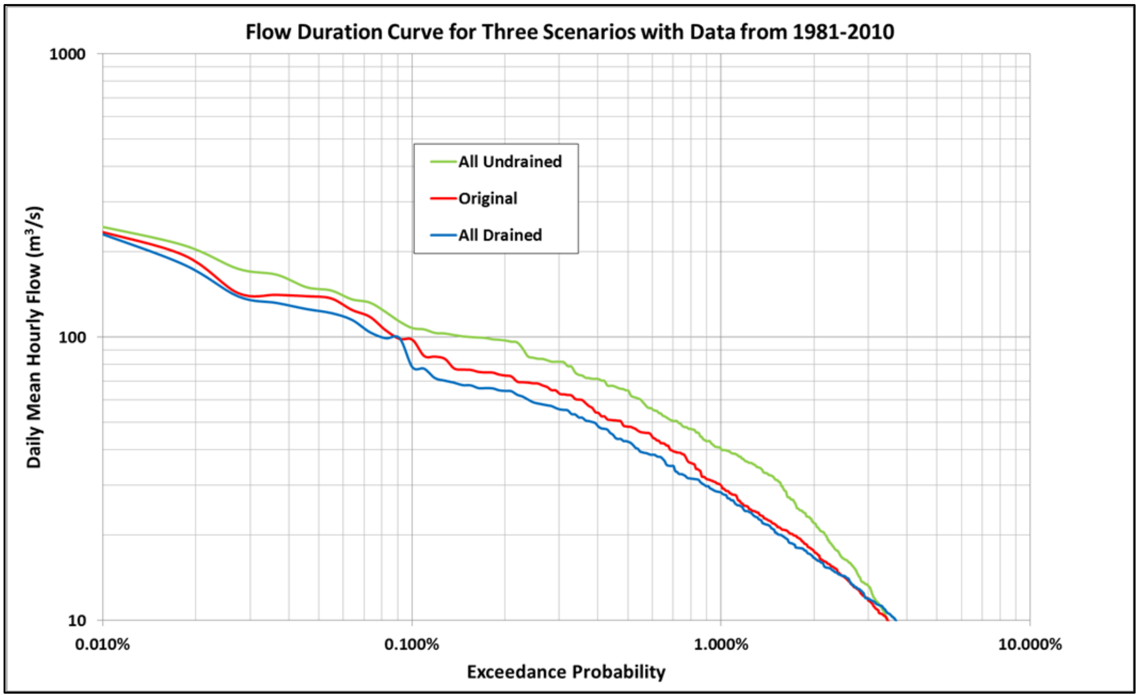


Figure 4-14 - Flow Duration Curve for three scenarios in the Clear Creek Watershed from 1981-2010.

4.3.4 The Role of Spatial Distribution of Subsurface Drainage on the Catchment Hydrologic Response

The results in Section 4.3.3 helped explain the impacts of tiles on the catchment hydrograph of the CCW by comparing the Original Scenario with the two end-member scenarios. Good overall conclusions were obtained through that analysis, but watersheds are not typically completely drained or undrained. Therefore, the location of tiled fields in a watershed needs to be studied in order to understand whether or not it has an impact on the catchment hydrograph. The first hydrograph analysis performed is the Far and Near Drainage scenario as compared to the All Undrained scenario. This analysis simply determines whether the location of tiles matters under the current assumed conditions of the CCW. The second hydrograph analysis performed is for more diagnostic purposes. The assumption was made that the CCW consists of one soil type, silt loam, and that 30% of the CCW is tiled. The Clustered Near and Clustered Far Drainage scenarios are compared in the second analysis in order to determine whether the clustering of tiled fields has an impact. Additionally, the second analysis removes the impacts of different soil types and verifies whether the results obtained in the first hydrograph analysis are still relevant. The final analysis is that of time integrated metrics, much as in Section 4.3.3.2.

4.3.4.1 Analysis of Event Hydrographs (Scenarios 4 and 5)

Once again, the events of August 1993 are used for this portion of the analysis of the All Undrained, Near, and Far Drainage scenarios. As a reminder, the Near and Far Drainage scenarios have the nearest and farthest 20% of total catchment area that have row crop land use drained. The reason these two scenarios are compared to the All Undrained is because it is the most extreme flow scenario. Below, in **Figure 4-15,** are the hydrographs for the three scenarios during the August events. As in Section 4.3.3.1, there is invariance in the August 10th hydrographs, but there are differences in the August 17th hydrographs. The mechanisms in the first event do not need to be explained further, since the explanation is the same as in Section 4.3.3.1, where tiling has no impact due to the large amount of surface runoff. Therefore, the August 17th hydrograph is utilized in this analysis.

There are a few important conclusions to draw from this initial spatial variability analysis of the August 17th hydrographs. The hydrograph of the All Undrained and Far Drainage scenarios are identical for most of August 16th, which makes sense because those are the fields from the lower portion of the CCW arriving at the outlet, which are all undrained. Then, on August 17th, both the Near Drainage and the All Undrained scenarios have nearly identical shapes and much higher peaks than the Far Drainage scenario, which also makes sense because the undrained fields that are located in the headwaters are arriving at the outlet during that time. Therefore, adding tile drainage in the headwaters causes a lower peak flow and creates a more uniform hydrograph. To help explain the mechanism behind this behavior, **Figure 4-16** shows the hydrographs of the three scenarios split up into the drained and undrained field components that contribute to the hydrographs.

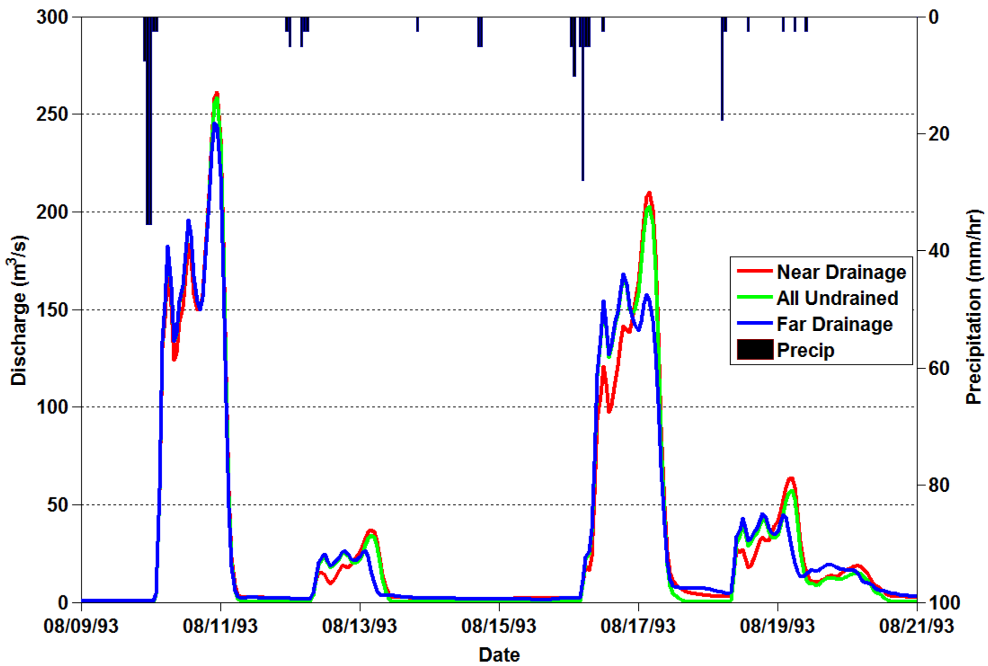
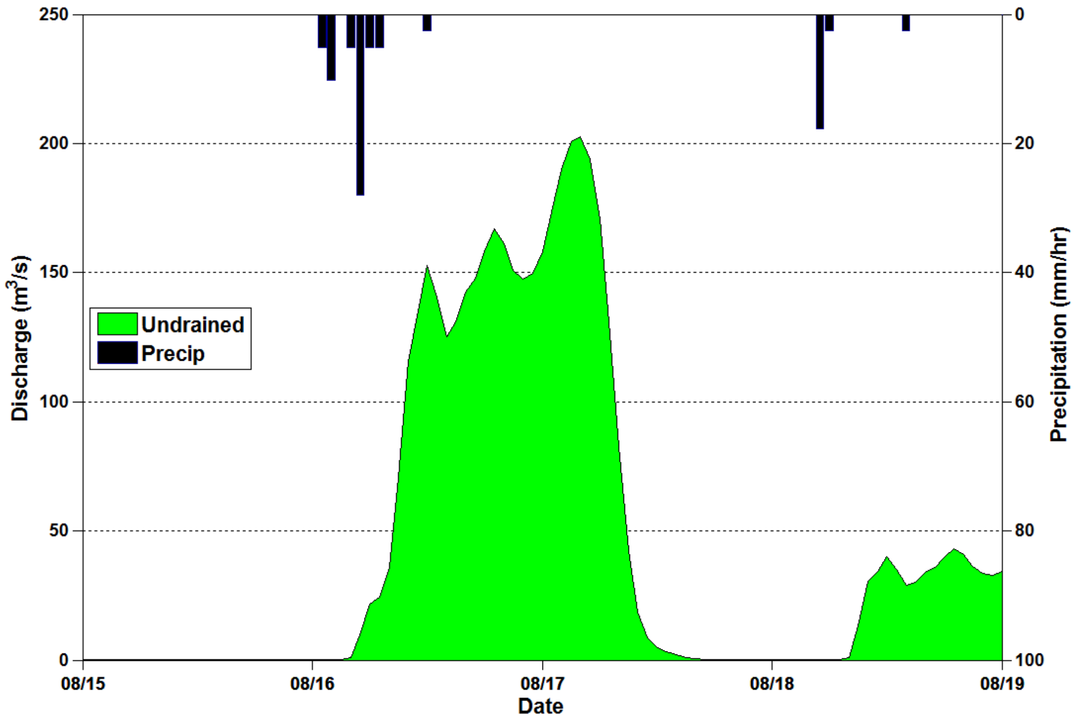


Figure 4-15 - August 1993 hydrographs for the All Undrained, Far, and Near Drainage.

The component hydrographs in **Figure 4-16** reveal how the drained fields are impacting tile drainage in this August event. The Near Drainage scenario (**Figure 4-16 B**) shows that the contribution of the drained fields occurs at the beginning of the event and that the hydrograph rise is gradual. The shape could possibly be a function of how dispersed the scenario's drained fields are (refer to **Figure 4-6**), meaning that the flows being routed from the drained fields cannot effectively synchronize due to their wide range of topologic distances from the outlet in the routing equation. This non-clustering issue will be dealt with in Section 4.3.4.2 but, for these scenarios, the assumption of drained field locations was based on which fields had row crop agriculture so that the results may be more realistic to the CCW. The Near Drainage scenario reveals that peaks in the earlier part of the hydrograph are decreased compared to the other two scenarios. This, once again, is because the drained fields are routing potentially fast surface runoff through the slower subsurface flow path. However, the later peak of the Near Drainage scenario is very large and is nearly the same as the All Undrained scenario. The Far Drainage scenario is the opposite of the Near Drainage: the peaks in the hydrograph are initially the same as the All Undrained but, during the highest peak, the flow is reduced by about 1,500 cfs. The reason for this reduction is that during the last peak, there are large contributions from drained fields (blue hydrograph in **Figure 4-16 C**) which, in this scenario, are reduced hydrographs compared to undrained fields. Additionally, it is important to note that though the total areas of drained fields in the two spatial scenarios are the same, the contributing hydrographs are not. Overall, the Far Drainage drained field hydrograph is more peaked than that of the Near Drainage. There are three possible explanations for the differing behaviors: 1) there are different soil types in the drained fields of both scenarios; 2) the Far Drainage's tiled fields are more clustered than those of the Near Drainage scenario; and 3) the stream network's width function has an influence. The first two will be addressed in Section 4.3.4.2, whereas the influence of the width function is important for understanding this overall hydrograph behavior and is discussed next.

There must be a reason why the last peak in the August 17th hydrograph is the greatest. One theory is that all flows are contributing once the furthest hillslope's flows reach the outlet. That may be true for scenarios in which there is more continuous rainfall over a longer period of time. However, for this shorter, more intense event, that explanation does not completely describe what is happening. Consideration of the Near Drainage scenario hydrograph (**Figure 4-16 B**) shows that the drained fields near the outlet are essentially finished contributing before the peak on August 17th, with the exception of slow tile flow. Considering that the Near Drainage scenario's drained fields

A) All Undrained



B) Near Drainage

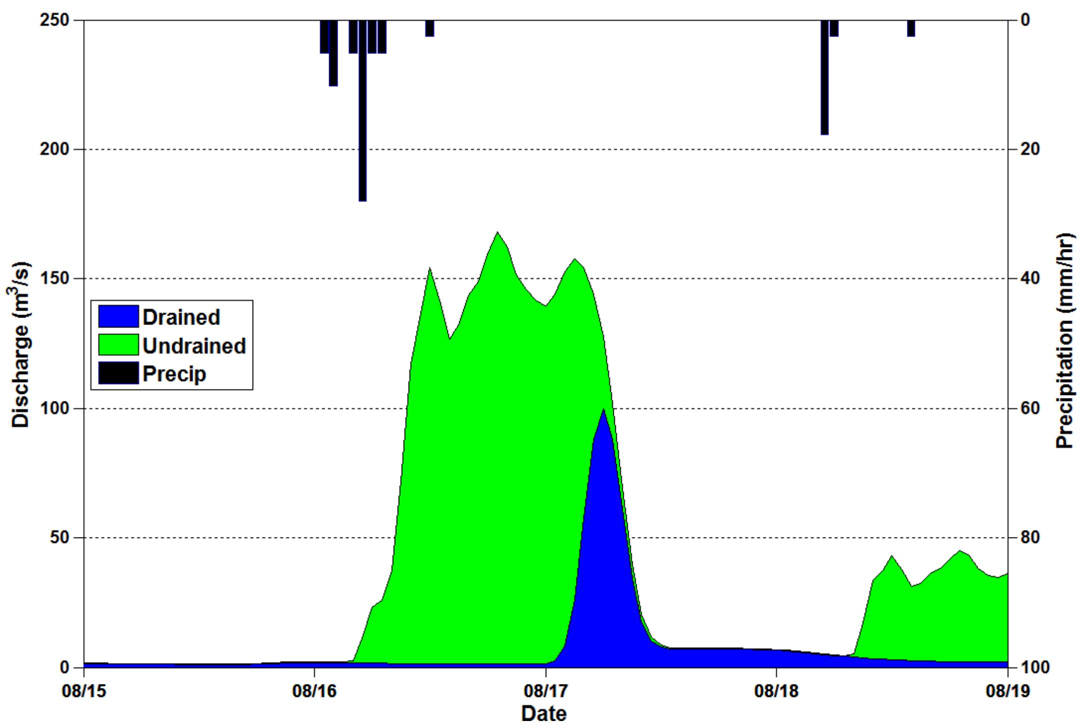


Figure 4-16 - Component hydrographs of the Drained and Undrained Fields for three design scenarios showing the influence of the spatial distribution of tiling.

C) Far Drainage

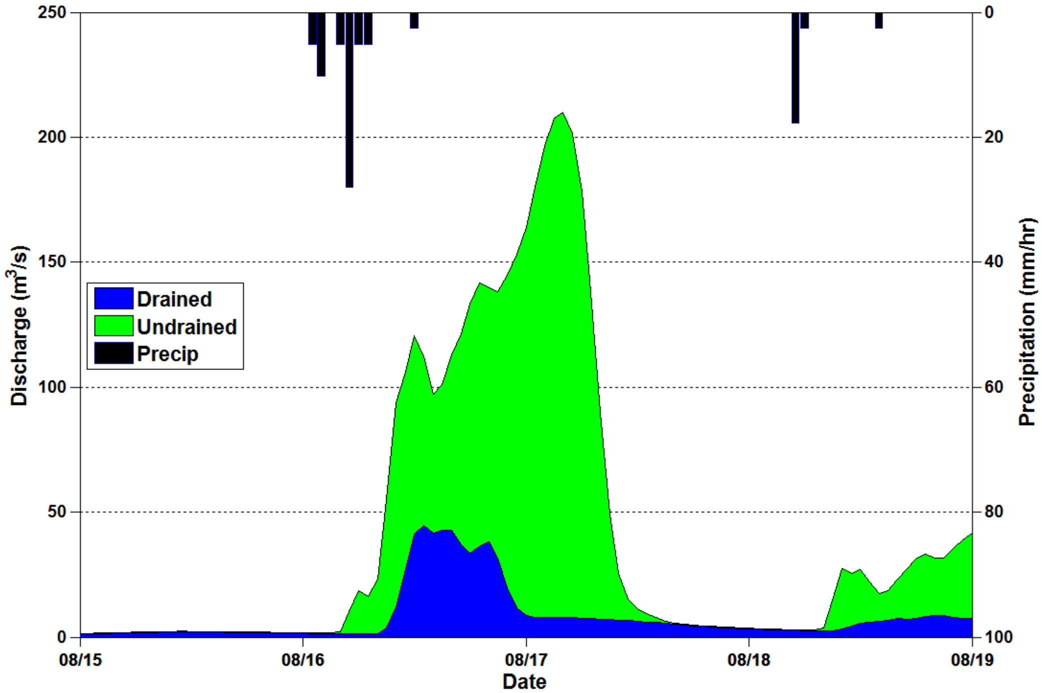


Figure 4-16 continued

are spread out over nearly half of the catchment width, it would be reasonable to say that the undrained fields at the same range of topologic distances would also be finished contributing before the peak on the 17th, given the similar duration of the undrained field hydrographs. Therefore, the final largest peak on August 17th is a function of the contributions of the fields in the headwaters and is largest because of the width function of the CCW stream network. The CCW width function is shown below in **Figure 4-17**. There is a noticeable cluster of hillslopes (each link is surrounded by a hillslope) from approximately 275-360 link lengths from the outlet. This is the area that is mainly contributing to the final peak and, more importantly, draining these hillslopes can give the most reduction in peak flows, as seen in the Far Drainage scenario. The peaks created at the outlet by this area of the width function are higher than others because the flows are allowed to synchronize due to the large amount hillslopes within a small range of topologic distances. The effect may be accentuated in this analysis, given the routing equation assumptions of a constant link length and velocity, but the behavior is still important to understand. According to this analysis of the CCW, the width function appears to dictate that the largest peak and tiled fields can have an impact in certain storm scenarios.

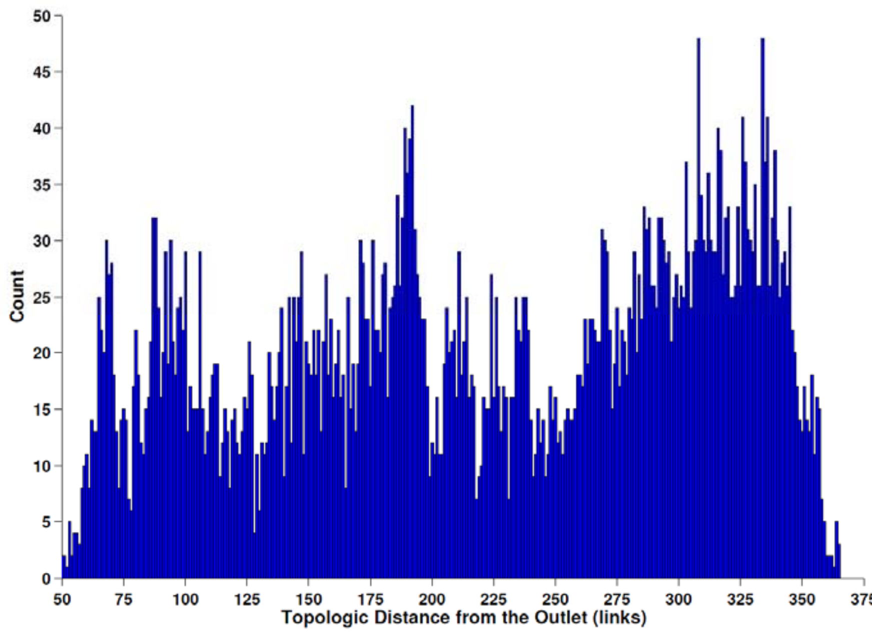


Figure 4-17 - Clear Creek Watershed Stream Network Width Function.

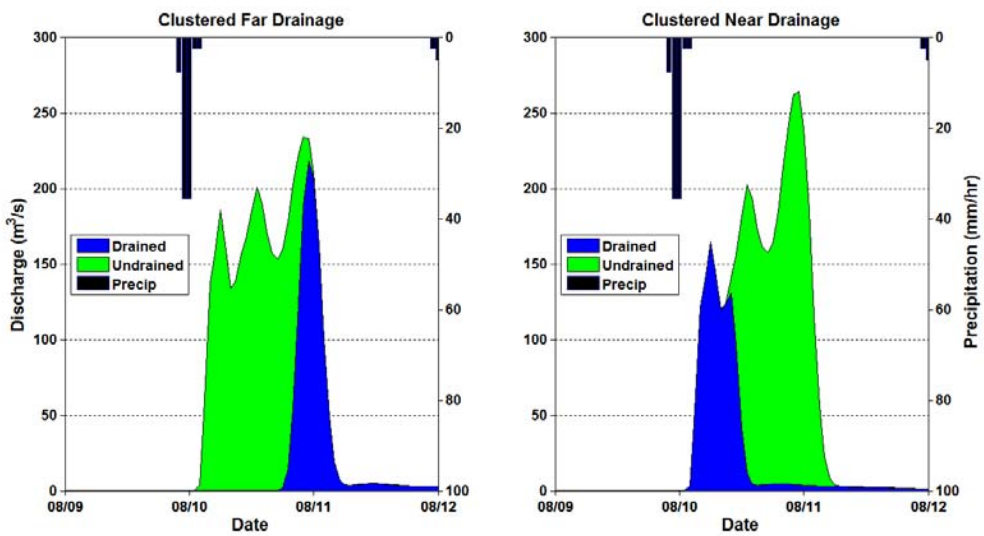
4.3.4.2 Analysis of Event Hydrographs (Scenarios 6 and 7)

The previous analysis in Section 4.3.4.1 concluded that for some large storm events, tiling in the headwaters can reduce the largest peak in the CCW. However, it is difficult to determine from those results the impact of the clustering of tiled fields and how important the soil types are to the observed behaviors. Therefore, the analysis in this section assumes a uniform soil type (silt loam) across the watershed and clusters the Near and Far Drainage scenarios to produce identical conditions for comparison. The Clustered Near and Far Drainage scenarios assume that the nearest and furthest hillslopes that make up 30% of the catchment area are drained (see **Figure 4-6**). For this analysis, both August events are analyzed because there are useful conclusions to be made from both events. The component hydrographs for both the Clustered Near and Clustered Far Drainage scenarios for both storm events are shown below in **Figure 4-18**.

The analysis of the two storms appears to show that the clustering of the tiles does, in fact, affect the drained field contribution hydrograph. The Clustered Near Drainage scenario's drained field contribution hydrograph is more peaked than in the original Near Drainage scenario. However, it is still not as peaked as the drained field contribution hydrograph of the Clustered Far Drainage scenario. This seems to indicate that the width function, as well as the clustering of tiled fields, influences the peakedness of these hydrographs. Additionally, these two storm events show that tiling in the headwaters will reduce the largest peak, which is dictated by the width function. This is a key difference from the previous analysis (Section 4.3.4.1) where the August 10th event hydrographs are invariant. This new result reveals that soil type can also be a key component in the impact of drained fields at the outlet, as expected.

The soil selected for this uniform spatial analysis was silt loam because nearly half the watershed consisted of this soil type. The reason that the August 10th storm event results are different for the Clustered events compared to the original scenarios can be explained by the field scale hydrographs for that event, as shown in **Figure 4-19**. The soil hillslope hydrographs for all of the soils are very similar for both the drained and undrained situations due to the large rainfall event and limited infiltration. However, tile drainage does have an impact on the silt loam hydrograph by reducing the peak by about 0.3 in/hr. Therefore, assuming the entire CCW is silt loam, the impact of the field scale hydrographs is seen at the outlet. Then, hypothetically, the more silt loam in the CCW, the larger rainfall-runoff events that could be impacted by tiling. The same could be said about adding loamy sand or sandy loam to the watershed, as those soils also saw a great reduction in field peaks from drainage. However, with the current assumed soil types of the CCW that were analyzed in Section 4.3.4.1, the amount of silt loam in the headwaters is not enough to reduce the peaks because the reduction is diluted by the other soil type hillslope hydrographs that are invariant with drainage. It is significant that the interplay among the soil type, width function, and rainfall event will dictate the outlet hydrograph.

A) August 10th Event



B) August 17th Event

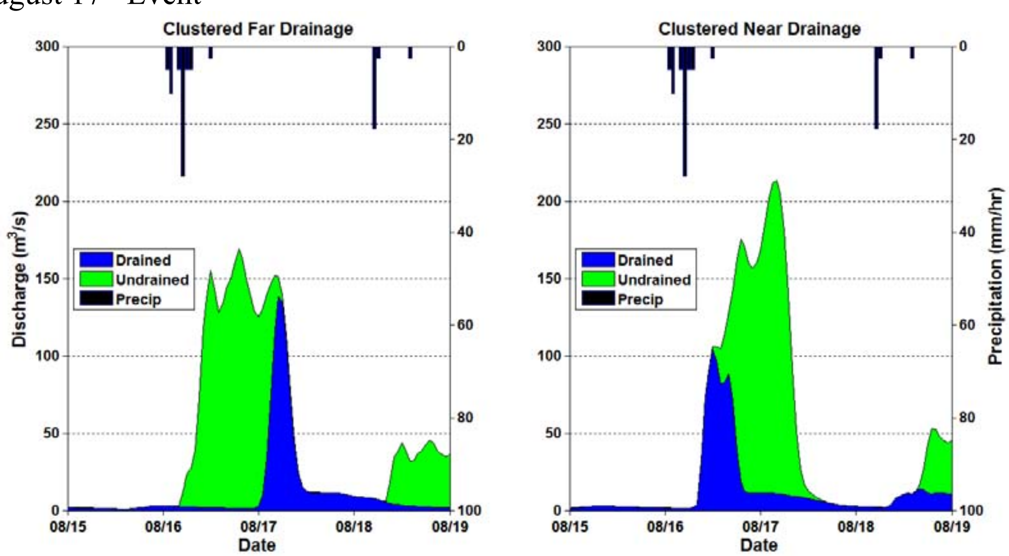
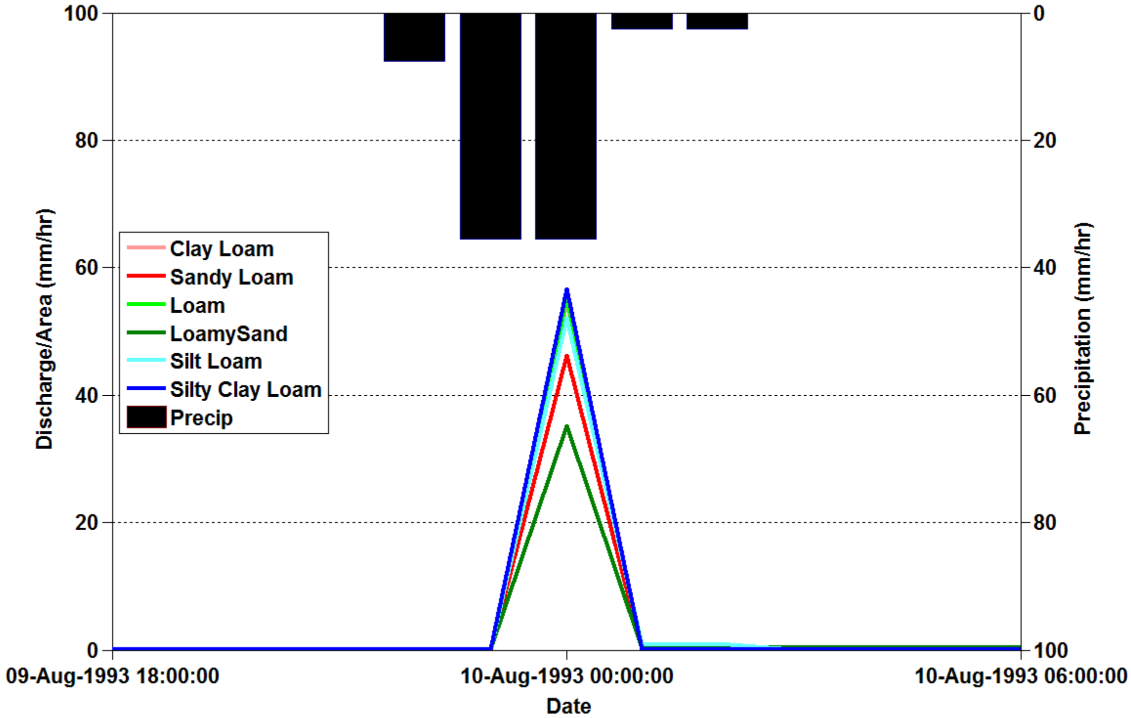


Figure 4-18 - Component hydrographs of the Clustered Near and Far Drainage scenarios for two August 1993 storm events.

A) Drained Field Hydrographs



B) Undrained Field Hydrographs

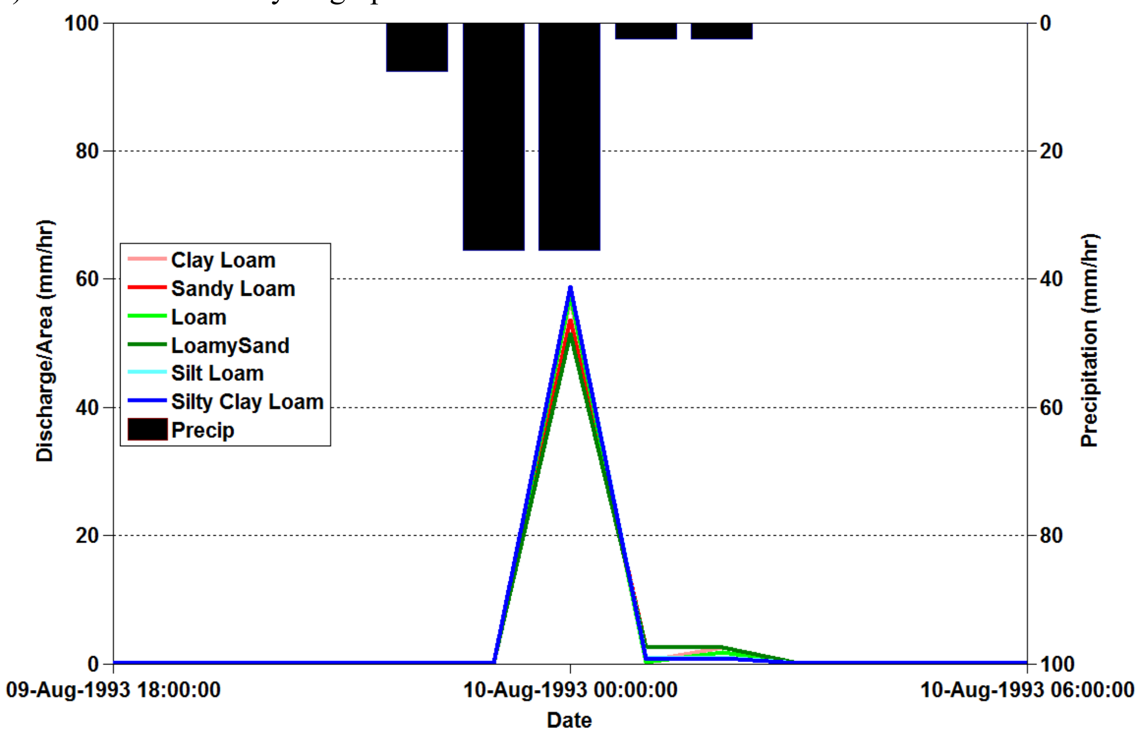


Figure 4-19 - August 10th Event Fields Scale Hydrographs of each soil type for drained and undrained fields.

4.3.4.3 Analysis of Flow Regime Shifts

The time integrated metrics give a more complete view of the impacts of the spatial distribution of tiling on the entire flow regime. These time integrated metrics are of the Far Drainage, Near Drainage, and All Undrained scenarios. The annual hourly peak flows for the CCW are shown below in **Figure 4-20**. Similar to Section 4.3.3, 20 of the 30 years have a peak reduction from the Far Drainage scenario. As mentioned above, the width function dictates the largest peak in the storm hydrographs, and for some large storm events, draining the headwaters reduces the largest peak flow. The remaining 10 years have invariance in the largest hourly flows because of the large amount of surface runoff, regardless of drainage or soil type.

The Flashiness Index, shown in **Figure 4-21**, tells a similar story to the hydrograph and peak flow analysis for the entire flow regime. The All Undrained and Near Drainage scenarios are close and are typically larger than the Far Drainage scenario. The years in which there appears to be invariance are typically drier years where the indicator is not very effective due to the limited rainfall-runoff events. The Flow Duration Curves (**Figure 4-22**) are also very similar to the results seen in Section 4.3.3.2. There is an inflection point around the 5% exceedance probability, indicating that the scenarios with drainage have higher flows at greater than 5% exceedance probability. At less than 5%, the flows of the three events do not differ by much, but their order from greatest to least is All Undrained, Near Drainage, and Far Drainage, respectively. Then, at very low exceedance probability (< 0.02%), the three FDCs are invariant.

4.4 Summary of the Catchment Scale Results

The analysis of the two August events and others that were not shown in this paper from the 30 years of model simulations displayed two separate behaviors. First, the effects of tiling are very small during very intense or large cumulative rainfall events, as indicated by the nearly identical hydrographs of the All Undrained, All Drained, and

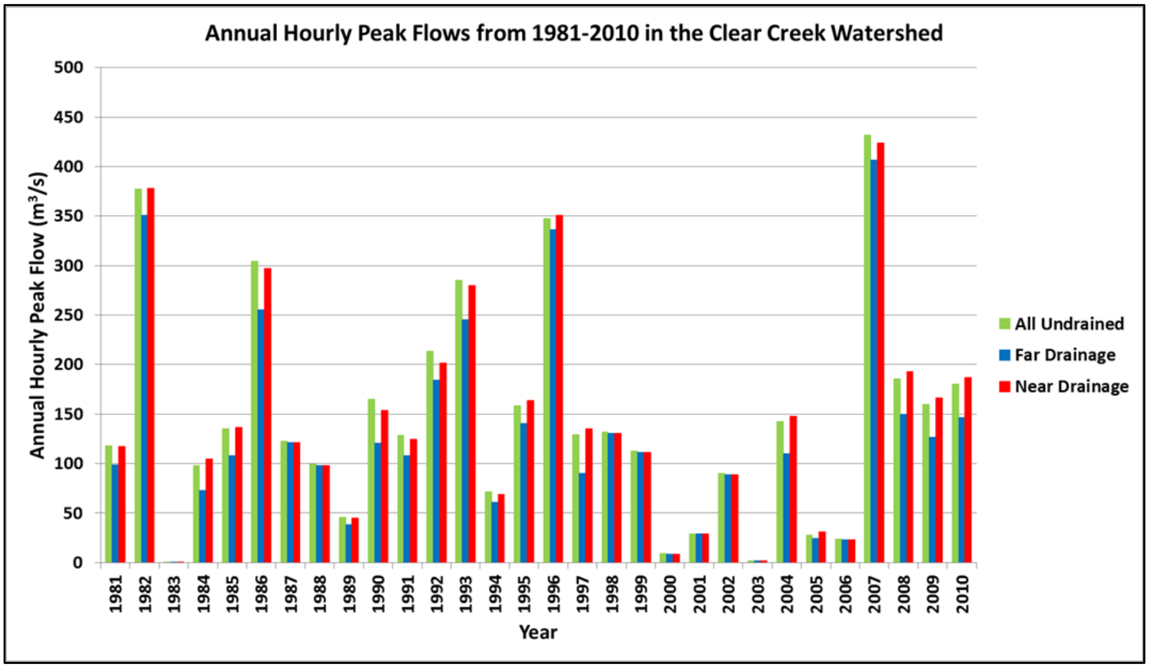


Figure 4-20 - Annual Hourly Peak flows for the All Drained, Far Drainage, and Near Drainage Scenario for the Clear Creek Watershed from 1981-2010.

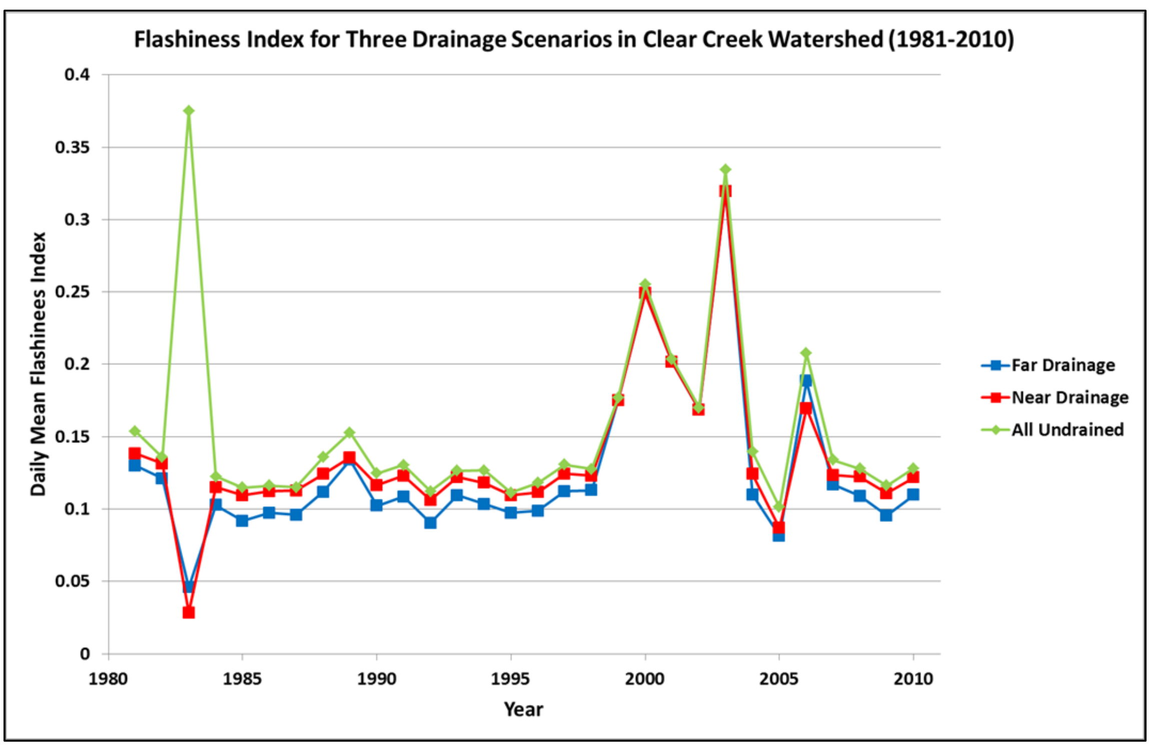


Figure 4-21 - Flashiness Index for the All Drained, Far Drainage, and Near Drainage Scenarios for the Clear Creek Watershed from 1981-2010.

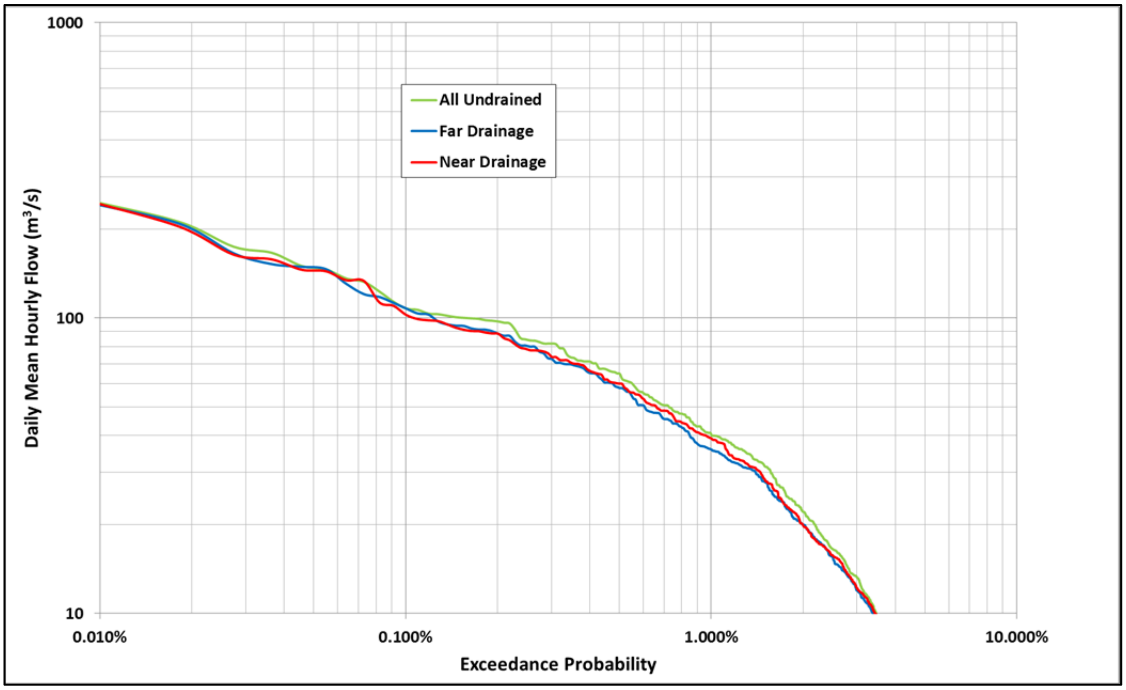


Figure 4-22 - Flow Duration Curves for the All Drained, Far Drainage, and Near Drainage Scenarios for the Clear Creek Watershed from 1981-2010.

Original scenarios. This is a function of all fields having the same surface runoff mechanism. Second, during some large storm events, the addition of tile drained fields to the CCW actually decreases the peaks. This conclusion is a function of the tiled fields reducing the amount of faster surface flow by allowing infiltration and a slower release from tiles. The greater the amount of tiling, the more visible the reduction is at the outlet.

The time integrated metrics gave a better perspective on the overall impact of tile drainage on the flow regime. The annual hourly peak flows showed that tiling was able to reduce the peaks for most years (about 2/3), while there was little impact for the other years (about 1/3). These two sets of years are representative of the behaviors described above, and their occurrence is due to a complex interplay of antecedent conditions, rainfall intensity and duration. The FI demonstrated that, for most years, the hydrographs resulting from the All Undrained scenario have higher peaks than those scenarios with tile drainage. This result means that for the majority of runoff events, tile drainage tends to decrease peaks in the CCW, which indicates that the signal that is apparent at the field scale hydrographs is visible at the outlet. The FDCs confirmed results from the hydrograph, peak flow, and FI analysis and provided some new perspective on low flows. For small probability events, the FDCs of all three scenarios are the same due to tiling having little to no impact. During the middle range of significant storm events, tiling reduced the amount of flow at the same exceedance probability. At low flows, however, the All Drained had the largest flow due to the tile drainage flow path being faster than the lateral seepage flow path in undrained fields. This behavior will typically be seen as baseflow after storm events.

The analysis of the spatial distribution of subsurface drainage on the catchment scale hydrograph response reiterated the mechanisms seen in Section 4.3.3 and revealed new ones. The observation that the width function plays a key role in the peak hydrograph production is very important. Consequently, the conclusion can be drawn that for certain storm events, putting tiled fields in the vital area of the runoff production of the width function can reduce peak flows. However, this is dependent upon the storm event, soil types, and clustering. The soil types will have different threshold storm events for which they can allow infiltration and slower subsurface routing. The example in this analysis assumed that the CCW was all silt loam soil. There was a noticeable reduction in the Clustered Far Drainage scenario for the August 10th event, whereas the hydrographs are invariant in the original all soil analysis (Section 4.3.4.1). Additionally, once the storm events overcome all soil infiltration or capacity thresholds, the field hydrographs become identical and tiling has no impact on the peaks that are dictated by the width function and rainfall amount.

CHAPTER 5: CONCLUSIONS AND FUTURE WORK

The overall objective of this thesis is to understand the impact of subsurface drainage on hydrologic response at the field and the catchment scales, with specific focus on the extensively tile-drained state of Iowa. This objective is achieved through an extensive literature review in Chapter 2, numerical simulations at the field-scale (~ 1 ha) in Chapter 3, and at catchment-scales (~260 km^2) in Chapter 4. Following are the primary conclusions from our analysis.

5.1 Impacts of Subsurface Drainage on Hydrologic Response at the Field-scale

At the field scale, the impacts of tile drainage are explored as a function of landscape (soil types and surface storage capacity), climatic (rainfall), and anthropogenic (drainage spacing) controls. Field scale simulations were run using DRAINMOD for three common Iowa soils (loam, silt loam, and silty clay loam) and three other soils to represent end-member conditions (clay, sand, and silt). For less permeable soils, the addition of tile drainage reduces the flashiness of the field by routing potential surface runoff through the subsurface. In contrast, for more permeable soils like sand, the addition of tiles can actually increase the flashiness of the system because the efficiency of the subsurface flow path, which is dominant before drainage, is increased. Sand is not typical to Iowa, but this behavior could possibly mimic macropores in Iowa Clay soils since DRAINMOD was not able to accurately model them. The difference between drained and undrained scenarios increases with increase in surface storage capacity for less permeable soils (clay and loam), while the difference is independent of surface storage capacity for sand.

The effect of soil type, however, is a function of the rainfall intensity. In Iowa, for the 75th percentile of the average daily normal rainfall for the April through September, the addition of tile drainage significantly decreases the daily flow rates for most of the state. In contrast, for the 25th percentile rainfall, the addition of tiles significantly increases daily flow rates. The results are mixed across the state, for the 50th percentile rainfall, with some areas of the state showing an increase and others showing a decrease. The significance testing on the drained and undrained field results during different daily storm events also indicate that around 30 to 35 mm of daily rainfall is the threshold at which there is not a significant difference between a drained and undrained field.

The tile spacing will not typically have an impact on annual peak flow, but it does impact the overall flow regime. The flashiness index metric demonstrates a saddle shape with drain spacing with an optimum spacing for the typical Iowa soils at which the FI is at a minimum. By decreasing drain spacing, infiltration is promoted and surface runoff is reduced, thus decreasing FI. However, if the drain spacing is too narrow, the amount of water being routed through the subsurface and out of the tiles becomes larger and increases the FI.

5.2 Impacts of Subsurface Drainage on Hydrologic Response at the Catchment-scale

At the catchment scale, the impacts of tile drainage are dependent upon the field scale controls mentioned above as well as the number and spatial distribution of tiled fields in the watershed. The catchment-scale analysis was performed in the Clear Creek Watershed (260 km^2) by routing the field-scale DRAINMOD hydrographs using an analytic expression of the scale dependent GIUH. The routing model was able to capture the hydrologic response based on the USGS data at the outlet of Clear Creek. The field-scale conclusions persisted at the catchment-scale, with subsurface drainage decreasing peak flows for most storm events. Further, the peak reduction was dependent on the spatial distribution of the drained fields in the catchment. More specifically, the location of the drained fields in the stream network's width function was found to be the most significant control on the hydrologic response. Draining fields located in the densest portion of the width function causes the greatest reduction in peaks, given that the drained fields have reduced peaks.

5.3 Future Work

There is future work that needs to be done both at the field, and the catchment scales. At the field scale, the DRAINMOD simulations should be run with more specific inputs and should be validated with field data if at all possible. The simplifications of the data input and of DRAINMOD itself are necessary, but they remove natural complexity. Additionally, this study was unable to cover the effects of macropores, which are very important during the summer months in less permeable clayey soils. The macropores can cause short circuiting of water flow to drain tiles and can cause larger peaks than surface runoff. DRAINMOD is unable to accurately describe macropore flow and, as a result of this as well as time constraints, it is left undone. Additionally, further analysis into the key characteristics of rainfall that drive the field and catchment scale behaviors would be useful. Defining the thresholds of storm characteristics for tiles with certain soils and spacings would be an extensive but groundbreaking project.

There is still much work to do at larger scales. The catchment scale analysis of this thesis applies only to catchments at the scale of 260 km^2. At this scale, the hourly field inputs being routed to the outlet still have an impact. However, at larger scales, the hourly field hydrographs may not matter due to the large storage times in the channels. Rather, the total volume of water leaving the fields may dictate the hydrograph at the outlet. Additionally, in order to truly understand the impacts of tile drainage, it is necessary to study catchments in which the assumption of a linear system does not apply. This first order catchment scale analysis should be compared to more complicated models and actual data in order to see how realistic the assumptions underlying it are.

Overall, the results in this thesis show that tiling can decrease peaks at both the field and catchment scales (< 260 km^2) for certain storm events. These results should be subject to further testing. However, this paper creates a framework by which the current understanding of tiling is more clearly explained, and it poses new conclusions about scaling results from the field to catchment scale. These results will hopefully advance understanding of the hydrology in Iowa and lead to greater conclusions and work in the future.

APPENDIX A: DRAINMOD MODEL INPUTS FOR DRAINED SILT LOAM

```
*******************************************************************************
                          D R A I N M O D   6.1

              Copyright 1980-2011 North Carolina State University
                          LAST UPDATE: January 2011
                           LANGUAGE FORTRAN 77/90

            DRAINMOD IS A FIELD-SCALE HYDROLOGIC MODEL DEVELOPED FOR
            THE DESIGN OF SUBSURFACE DRAINAGE SYSTEMS. THE MODEL WAS
            DEVELOPED BY RESEARCHERS AT THE DEPT. OF BIOLOGICAL AND
            AGRICULTURAL ENGINEERING, NORTH CAROLINA STATE UNIVERSITY
            UNDER THE DIRECTION OF R. W. SKAGGS.
*******************************************************************************


 DATA READ FROM INPUT FILE: C:\DrainMod\inputs\MultiscaleInputs\Drained\Silt
 Cream selector (0=no, 1=yes) =  0

                        TITLE OF RUN
                        ************


 Clay Soil
 The soil is in a drained state


                       CLIMATE INPUTS
                       ******* ******

      DESCRIPTION                              (VARIABLE)     VALUE   UNIT
 -------------------------------------------------------------------------------
 FILE FOR RAINDATA ..............C:\DrainMod\weather\IowaCity81_2011.RAI
 FILE FOR TEMPERATURE/PET DATA ..C:\DrainMod\weather\IowaCitytemp81_2011.TEM
 RAINFALL STATION NUMBER..........................(RAINID)     134101
 TEMPERATURE/PET STATION NUMBER...................(TEMPID)     134101
 STARTING YEAR OF SIMULATION..................(START YEAR)       1981   YEAR
 STARTING MONTH OF SIMULATION................(START MONTH)          1   MONTH
 ENDING YEAR OF SIMULATION......................(END YEAR)       2010   YEAR
 ENDING MONTH OF SIMULATION....................(END MONTH)         12   MONTH
 TEMPERATURE STATION LATITUDE...................(TEMP LAT)      42. 7   DEG.MIN
 HEAT INDEX..........................................(HID)      44.00


 ET MULTIPLICATION FACTOR FOR EACH MONTH
    1.30  1.30   .60   .60   .60   .80   .90   .90  1.20  1.30  1.30  1.30
```

```
                              DRAINAGE SYSTEM DESIGN
                               **********************

                             *** CONVENTIONAL DRAINAGE ***

          JOB TITLE:

                   Clay Soil
                   The soil is in a drained state

                    STMAX = 1.25 CM                    SOIL SURFACE
+         __/)____________________________________________________________/)__
              :                                                    :
              :                                                    :
              :                                                    :
           ADEPTH =390.  CM                                     DDRAIN =106.  CM
              :                                                    :
              :     O-------------SDRAIN = 2000.  CM -----------O  -
              :     *                                              :
              : EFFRAD =1.50 CM                                    :
              :                                                 HDRAIN =117.  CM
              :                                                    :
          - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
              :
              :
              :                                        IMPERMEABLE LAYER
+         _____________________________________________________________________
          /////////////////////////////////////////////////////////////////////


                    DEPTH       SATURATED HYDRAULIC CONDUCTIVITY
                    (CM)                      (CM/HR)

                   .0 -   390.0                1.090


DEPTH TO DRAIN = 106.0 CM
EFFECTIVE DEPTH FROM DRAIN TO IMPERMEABLE LAYER = 117.4 CM
DISTANCE BETWEEN DRAINS =  2000.0 CM
MAXIMUM DEPTH OF SURFACE PONDING =  1.25 CM
EFFECTIVE DEPTH TO IMPERMEABLE LAYER =  223.4 CM
DRAINAGE COEFFICIENT(AS LIMITED BY SUBSURFACE OUTLET) =  1.30 CM/DAY
MAXIMUM PUMPING CAPACITY (SUBIRRIGATION MODE) =   2.50 CM/DAY
ACTUAL DEPTH FROM SURFACE TO IMPERMEABLE LAYER = 390.0 CM
SURFACE STORAGE THAT MUST BE FILLED BEFORE WATER
  CAN MOVE TO DRAIN =  .25 CM
FACTOR -G- IN KIRKHAM EQ. 2-17 =10.01

  *** SEEPAGE LOSS INPUTS ***

   No seepage due to field slope

   Vertical Deep Seepage
      hydraulic head in aquifer (cm)=      250.000000
      thickness of impeading layer (cm)=      250.000000
      vertical conductivity of impeading layer (cm/hr)=    2.200000E-04

   Lateral Deep Seepage
       thickness of convenance layer (cm)=    0.000000E+00
       hydraulic head at offsite sink/source (cm)=      284.000000
       distance to offsite sink/source (cm)=    10000.000000
       lateral conductivity of conveyance layer (cm/hr)=       1.090000

 *** end of seepage inputs ***
```

WIDTH OF DITCH BOTTOM = 200.0 CM
SIDE SLOPE OF DITCH (HORIZ:VERT) = .50 : 1.00

INITIAL WATER TABLE DEPTH = 110.0 CM

DEPTH OF WEIR FROM THE SURFACE

DATE	1/ 1	2/ 1	3/ 1	4/ 1	5/ 1	6/ 1
WEIR DEPTH	106.0	106.0	106.0	106.0	106.0	106.0

DATE	7/ 1	8/ 1	9/ 1	10/ 1	11/ 1	12/ 1
WEIR DEPTH	106.0	106.0	106.0	106.0	106.0	106.0

SOIL INPUTS
****

TABLE 1

DRAINAGE TABLE

VOID VOLUME (CM)	WATER TABLE DEPTH (CM)
.0	.0
1.0	82.3
2.0	108.6
3.0	129.2
4.0	146.6
5.0	160.3
6.0	173.2
7.0	186.0
8.0	198.9
9.0	206.4
10.0	213.4
11.0	220.4
12.0	227.4
13.0	234.4
14.0	241.3
15.0	248.3
16.0	255.3
17.0	262.3
18.0	269.3
19.0	276.3
20.0	283.3
21.0	290.3
22.0	297.3
23.0	304.3
24.0	311.3
25.0	318.3
26.0	325.3
27.0	332.3
28.0	339.3
29.0	346.2
30.0	353.2
35.0	388.2
40.0	423.2
45.0	458.1
50.0	493.1
60.0	592.0
70.0	694.0
80.0	796.0
90.0	898.0

TABLE 2

SOIL WATER CHARACTERISTIC VS VOID VOLUME VS UPFLUX

HEAD (CM)	WATER CONTENT (CM/CM)	VOID VOLUME (CM)	UPFLUX (CM/HR)
.0	.4390	.00	.5000
10.0	.4370	.01	.5000
20.0	.4350	.04	.5000
30.0	.4322	.09	.5000
40.0	.4286	.17	.5000
50.0	.4250	.30	.5000
60.0	.4202	.45	.5000
70.0	.4154	.67	.4264
80.0	.4104	.93	.3559
90.0	.4052	1.23	.2886
100.0	.4000	1.64	.2469
110.0	.3948	2.06	.2052
120.0	.3896	2.47	.1635
130.0	.3844	3.05	.1449
140.0	.3792	3.62	.1264
150.0	.3740	4.20	.1078
160.0	.3690	4.97	.0979
170.0	.3640	5.75	.0880
180.0	.3590	6.53	.0780
190.0	.3540	7.31	.0681
200.0	.3490	8.09	.0582
210.0	.3450	9.52	.0564
220.0	.3410	10.95	.0546
230.0	.3370	12.38	.0528
240.0	.3330	13.81	.0510
250.0	.3290	15.24	.0492
260.0	.3250	16.67	.0474
270.0	.3210	18.10	.0456
280.0	.3170	19.53	.0438
290.0	.3130	20.96	.0420
300.0	.3090	22.39	.0402
350.0	.2918	29.54	.0313
400.0	.2789	36.69	.0223
450.0	.2659	43.84	.0133
500.0	.2530	50.99	.0043
600.0	.2404	60.79	.0034
700.0	.2278	70.59	.0026
800.0	.2152	80.39	.0017
900.0	.2026	90.20	.0009

GREEN AMPT INFILTRATION PARAMETERS

W.T.D. (CM)	A (CM)	B (CM)
.000	.000	.070
10.000	.010	.070
20.000	.020	.070
40.000	.050	.070
60.000	.090	.070
80.000	.130	.070
100.000	.180	.070
150.000	1.600	.070
200.000	1.600	.070
1000.000	1.600	.070

TRAFFICABILITY
****

REQUIREMENTS	FIRST PERIOD	SECOND PERIOD
-MINIMUM AIR VOLUME IN SOIL (CM):	4.40	4.40
-MAXIMUM ALLOWABLE DAILY RAINFALL(CM):	1.20	1.20
-MINIMUM TIME AFTER RAIN BEFORE TILLING CAN CONTINUE:	2.00	2.00
WORKING TIMES		
-DATE TO BEGIN COUNTING WORK DAYS:	4/33	12/35
-DATE TO STOP COUNTING WORK DAYS:	4/33	12/35
-FIRST WORK HOUR OF THE DAY:	8	8
-LAST WORK HOUR OF THE DAY:	20	20

CROP
****

SOIL MOISTURE AT WILTING POINT = .11

HIGH WATER STRESS: BEGIN STRESS PERIOD ON 3/15
END STRESS PERIOD ON 11/15
CROP IS IN STRESS WHEN WATER TABLE IS ABOVE 30.0 CM

DROUGHT STRESS: BEGIN STRESS PERIOD ON 3/15
END STRESS PERIOD ON 11/15

MO	DAY	ROOTING DEPTH(CM)
1	1	3.0
3	11	11.0
3	21	15.0
3	31	15.0
4	29	15.0
5	2	3.0
6	3	3.0
6	12	3.0
6	28	7.0
7	16	7.0
8	2	25.0
8	19	33.0
8	27	35.0
9	6	36.0
9	20	21.0
9	26	6.0
12	31	3.0

WASTEWATER IRRIGATION
****

NO WASTEWATER IRRIGATION SCHEDULED:

***** No Wetlands Criteria ******

Fixed Monthly Pet Values

1 1.00 2 1.00 3 1.00 4 1.00 5 1.00 6 1.00
7 1.00 8 1.00 9 1.00 10 1.00 11 1.00 12 1.00

```
  Mrank indicator =  0


 SOIL TEMPERATURE AND SNOWMELT INPUT PARAMETERS
   Za       Zb       TK_a       TK_b       TB       TLAG       TSNOW  TMELT   CDEG     C_ICE
   2.500    1.206     .390    1.326      7.2      8.0       .0      2.0      5.0      .20
 Initial soil temperature profile
 Initial snow depth(m) initial snow density(kg/m3)
    0.000000E+00      100.000000
 SOIL WATER CHARACTERISTIC CURVE
 NUMBER OF LAYERS:            1
 TLAYER    BLAYER
    .00  390.00
        12
   .439       .0
   .434     25.0
   .425     50.0
   .413     75.0
   .400    100.0
   .374    150.0
   .349    200.0
   .297    330.0
   .253    500.0
   .190   1000.0
   .109   5000.0
   .086 15000.0
 FREEZING CHARACTERISTIC CURVE
 NUMBER OF POINTS:           11
      .0     .393
    -1.0     .170
    -2.0     .140
    -3.0     .111
    -4.0     .081
    -5.0     .053
    -6.0     .023
    -7.0     .000
    -8.0     .000
    -9.0     .000
   -10.0     .000
   ****************** NEW CROP *********************
C:\DrainMod\crops\Websorigcorn.cin
  CROP ROTATION NUMBER:   1

 DAY TO BEGIN WORKING FIELD: 105     DAY TO FINISH HARVESTING FIELD: 335
  INWEIR =   1


     DEPTH OF WEIR FROM THE SURFACE
     ------------------------------
 DATE          1/  1    2/  1    3/  1    4/  1    5/  1    6/  1
 WEIR DEPTH    106.0    106.0    106.0    106.0    106.0    106.0

 DATE          7/  1    8/  1    9/  1    10/  1   11/  1   12/  1
 WEIR DEPTH    106.0    106.0    106.0    106.0    106.0    106.0



                              TRAFFICABILITY
                              **************

                                                            FIRST        SECOND
    REQUIREMENTS                                            PERIOD       PERIOD
       -MINIMUM AIR VOLUME IN SOIL (CM):                     2.50         2.50
       -MAXIMUM ALLOWABLE DAILY RAINFALL(CM):                1.50         1.50
       -MINIMUM TIME AFTER RAIN BEFORE TILLING CAN CONTINUE: 2.00         2.00
```

```
WORKING TIMES
   -DATE TO BEGIN COUNTING WORK DAYS:                          4/15        9/15
   -DATE TO STOP COUNTING WORK DAYS:                           6/ 5       11/ 0
   -FIRST WORK HOUR OF THE DAY:                                 6           6
   -LAST WORK HOUR OF THE DAY:                                 18          18


                                   CROP
                                   ****


HIGH WATER STRESS:   BEGIN STRESS PERIOD ON    4/15
                     END STRESS PERIOD ON     10/20
                     CROP IS IN STRESS WHEN WATER TABLE IS ABOVE   30.0 CM

DROUGHT STRESS:      BEGIN STRESS PERIOD ON    4/15
                     END STRESS PERIOD ON     10/20


                              MO    DAY    ROOTING DEPTH(CM)
                               1     1         3.0
                               5    10         3.0
                               6     1        15.0
                               6    20        30.0
                               7     2        45.0
                               7    17        60.0
                               8    30        60.0
                               9    15        45.0
                              10     1        30.0
                              10    15         3.0
                              12    31         3.0

                                 YIELD INPUTS
                                 ************

 last planting day without yield loss (JLAST):        140
 length of growing season (IGROW)            :        165
 1st planting day reduction factor (PDRF)    :   7.600000E-01
 days using 1st planting delay fact (DELAY1) :     30.000000
 2nd planting day reduction factor (PDRF2)   :      2.100000
 total days of work before planting (REQWRK) :      1.000000
 IOW:          32
 IOH:          10
 YSLOPE:        1.220000
 YRDMAX:      100.000000
 DSLOPE:    1.700000E-01
 PD :         130
 IGR:         160
 SDF:           1
 IPS(I),IPE(I),CSD(I),I=1,IOH
    0     9        .2000
   10    29        .2100
   30    39        .2300
   40    49        .2700
   50    59        .3100
   60    69        .2800
   70    79        .2000
   80    99        .1400
  100   119        .1000
  120   165        .0600
 CSI(I),I=1,IOW
           .0000        .0000        .0000        .0000        .0000
           .0000        .5000        .5000       1.0000       1.0000
          1.0000       1.0000       1.7500       2.0000       2.0000
          2.0000       2.0000       2.0000       2.0000       2.0000
          1.3000       1.3000       1.3000       1.3000       1.3000
          1.2000       1.0000        .5000        .0000        .0000
           .0000        .0000
```

```
******************************** END OF INPUTS ********************************

 ----------RUN STATISTICS ----------          time:  7/19/2013  @ 17:57
input file:   C:\DrainMod\inputs\MultiscaleInputs\Drained\Silt
parameters:    free drainage              and yields calculated
              drain spacing =    2000. cm   drain depth =  106.0 cm
-----------------------------------------------------------------------



**> Computational Statistics       <**
**> Start Computations    =1077.138
**> End Computations      =1077.162
**> Total simulation time =     1.5 seconds.
```

APPENDIX B: P-VALUES FOR IOWA RAINFALL ANALYSIS

Below are the p-values for Scenario 1 in Section 3.4.2 which only use days with undrained field flows greater than 0.1 mm/yr. The sand t-test was run for with a null hypothesis of drained fields being greater than undrained fields unlike the other soils. The red highlighted cells indicate values less than 0.05 while the green cells indicate values greater than 0.95.

Table B-1 - P-values of four Iowa soils from the Scenario 1 rainfall analysis in Section 3.4.2

Sand			Loam			Silt Loam			Silt Clay Loam		
Daily Precip (in.)	Count	P-value	Daily Precip (in.)	Count	P-value	Daily Precip (in.)	Count	P-value	Daily Precip (in.)	Count	P-value
0.1	528	4.52E-07	0.1	66	8.64E-01	0.1	82	9.92E-01	0.1	64	8.56E-01
0.2	222	1.70E-04	0.2	34	2.24E-01	0.2	41	6.64E-01	0.2	33	3.52E-01
0.3	150	7.08E-05	0.3	30	8.78E-02	0.3	37	2.85E-01	0.3	32	3.94E-02
0.4	103	2.15E-05	0.4	35	7.10E-08	0.4	36	1.49E-05	0.4	33	2.96E-06
0.5	70	2.08E-03	0.5	22	4.23E-03	0.5	28	2.11E-02	0.5	24	3.98E-02
0.6	65	5.02E-02	0.6	18	9.27E-03	0.6	23	2.51E-02	0.6	18	3.42E-02
0.7	58	4.80E-05	0.7	23	1.18E-06	0.7	30	3.99E-05	0.7	23	2.30E-05
0.8	43	1.19E-04	0.8	21	1.96E-05	0.8	25	1.14E-05	0.8	21	2.94E-04
0.9	39	8.56E-04	0.9	18	2.74E-05	0.9	21	5.37E-04	0.9	17	6.55E-04
1	31	2.28E-01	1	19	1.92E-03	1	20	5.57E-03	1	19	8.04E-03
1.1	17	1.82E-03	1.1	14	2.42E-03	1.1	13	3.66E-04	1.1	13	4.15E-03
1.2	21	2.25E-02	1.2	19	5.22E-03	1.2	16	3.68E-02	1.2	19	3.78E-02
1.3	16	1.68E-01	1.3	8	3.79E-02	1.3	10	5.42E-02	1.3	9	9.11E-02
1.4	16	6.79E-03	1.4	12	8.21E-02	1.4	9	1.36E-01	1.4	10	1.20E-01
1.5	9	2.57E-02	1.5	9	4.06E-02	1.5	7	1.80E-02	1.5	9	1.60E-01
1.6	14	4.92E-01	1.6	11	9.73E-02	1.6	12	1.74E-01	1.6	11	1.14E-01
1.7	7	7.02E-02	1.7	4	1.42E-01	1.7	4	1.59E-01	1.7	4	1.72E-01
1.8	7	8.01E-02	1.8	8	1.24E-01	1.8	8	1.51E-01	1.8	8	1.34E-01
1.9	3	7.11E-01	1.9	3	2.86E-01	1.9	3	2.03E-01	1.9	3	3.26E-01
2	6	1.88E-01	2	7	1.72E-01	2	7	3.35E-01	2	7	2.74E-01
2.1	4	7.91E-01	2.1	4	2.07E-01	2.1	4	3.55E-01	2.1	4	2.36E-01
2.2	8	5.27E-01	2.2	9	3.74E-01	2.2	8	3.63E-01	2.2	9	4.15E-01
2.3	3	1.96E-01	2.3	3	2.16E-01	2.3	3	3.00E-01	2.3	3	2.47E-01
2.4	2	7.30E-01	2.4	3	2.40E-01	2.4	3	2.79E-01	2.4	3	2.31E-01
2.5	2	5.87E-01	2.5	2	1.05E-01	2.5	2	2.00E-01	2.5	2	1.57E-01
2.8	3	6.63E-01	2.6	1	NaN	2.6	1	NaN	2.6	1	NaN
3	1	NaN	2.7	2	5.00E-01	2.7	2	5.00E-01	2.7	2	5.00E-01
3.3	2	7.05E-01	2.8	4	2.11E-01	2.8	4	3.22E-01	2.8	5	3.00E-01
3.5	1	NaN	3	1	NaN	3	1	NaN	3	1	NaN
4.3	1	NaN	3.3	2	2.06E-01	3.3	2	3.24E-01	3.3	2	2.26E-01
6.2	1	NaN	3.4	1	NaN	3.4	1	NaN	3.4	1	NaN
-	-	-	3.5	1	NaN	3.5	1	NaN	3.5	1	NaN
-	-	-	4.3	1	NaN	4.3	1	NaN	3.8	1	NaN
-	-	-	6.2	1	NaN	6.2	1	NaN	4.3	1	NaN
-	-	-	-	-	-	-	-	-	6.2	1	NaN

Table B-2 - P-values of three additional Iowa soils from the Scenario 1 rainfall analysis in Section 3.4.2

Silty Clay			Loamy Sand			Clay Loam		
Daily Precip (in.)	Count	P-value	Daily Precip (in.)	Count	P-value	Daily Precip (in.)	Count	P-value
0.1	65	4.52E-01	0.1	389	1.00E+00	0.1	68	4.94E-01
0.2	38	1.82E-02	0.2	166	9.97E-01	0.2	37	2.65E-02
0.3	30	3.67E-03	0.3	115	8.88E-01	0.3	33	9.34E-03
0.4	32	1.72E-07	0.4	81	4.27E-01	0.4	32	5.76E-09
0.5	26	2.22E-03	0.5	50	1.69E-01	0.5	22	1.61E-03
0.6	16	5.70E-02	0.6	44	2.26E-01	0.6	16	2.03E-02
0.7	25	4.14E-06	0.7	43	2.17E-01	0.7	23	8.21E-06
0.8	23	1.06E-04	0.8	32	3.75E-03	0.8	23	1.59E-06
0.9	21	2.20E-04	0.9	26	1.09E-02	0.9	18	8.95E-05
1	19	8.96E-03	1	22	7.24E-03	1	18	8.19E-04
1.1	15	7.19E-03	1.1	12	1.00E-01	1.1	13	8.60E-04
1.2	22	5.58E-03	1.2	17	5.45E-02	1.2	19	2.30E-03
1.3	11	4.16E-02	1.3	11	2.35E-01	1.3	9	1.52E-02
1.4	13	5.80E-02	1.4	13	8.03E-02	1.4	10	8.21E-02
1.5	10	9.24E-02	1.5	8	5.27E-02	1.5	8	5.13E-02
1.6	13	1.21E-01	1.6	12	2.13E-01	1.6	12	9.65E-02
1.7	4	1.27E-01	1.7	6	6.00E-01	1.7	4	1.54E-01
1.8	8	1.82E-01	1.8	6	7.23E-02	1.8	8	8.32E-02
1.9	3	2.90E-01	1.9	2	2.74E-01	1.9	3	3.26E-01
2	7	2.15E-01	2	7	3.17E-01	2	7	1.39E-01
2.1	4	1.87E-01	2.1	3	1.03E-01	2.1	4	1.64E-01
2.2	9	3.81E-01	2.2	8	1.93E-01	2.2	9	2.82E-01
2.3	3	3.27E-01	2.3	3	1.91E-01	2.3	3	2.19E-01
2.4	4	3.37E-01	2.4	3	1.48E-01	2.4	3	2.66E-01
2.5	2	6.08E-02	2.5	2	2.86E-01	2.5	2	1.25E-01
2.6	1	NaN	2.6	1	NaN	2.6	1	NaN
2.7	2	4.49E-01	2.8	3	7.47E-02	2.7	2	3.70E-01
2.8	5	1.98E-01	3	1	NaN	2.8	4	1.90E-01
3	1	NaN	3.3	2	0.203166	3	1	NaN
3.3	2	1.77E-01	3.5	1	NaN	3.3	2	2.45E-01
3.4	1	NaN	4.3	1	NaN	3.4	1	NaN
3.5	1	NaN	6.2	1	NaN	3.5	1	NaN
3.8	1	NaN	-	-	-	4.3	1	NaN
4.3	1	NaN	-	-	-	6.2	1	NaN
6.2	1	NaN	-	-	-	-	-	-

Below are the p-values for Scenario 2 in Section 3.4.2 which only use days with drained field flows greater than 0.1 mm/yr. The sand t-test was run for with a null hypothesis of drained fields being greater than undrained fields unlike the other soils. The red highlighted cells indicate values less than 0.05 while the green cells indicate values greater than 0.95.

Table B-3 - P-values of four Iowa soils from the Scenario 2 rainfall analysis in Section 3.4.2

Sand			Loam			Silt Loam			Silt Clay Loam		
Daily Precip (in.)	Count	P-value	Daily Precip (in.)	Count	P-value	Daily Precip (in.)	Count	P-value	Daily Precip (in.)	Count	P-value
0.1	191	5.35E-21	0.1	276	1.00E+00	0.1	225	1.00E+00	0.1	233	1.00E+00
0.2	93	2.92E-10	0.2	109	8.81E-01	0.2	93	9.53E-01	0.2	91	8.71E-01
0.3	67	7.55E-09	0.3	76	4.07E-01	0.3	65	5.31E-01	0.3	70	2.97E-01
0.4	57	3.61E-09	0.4	60	1.84E-04	0.4	55	2.24E-03	0.4	50	1.24E-03
0.5	36	1.38E-05	0.5	33	1.55E-02	0.5	33	6.21E-02	0.5	30	7.32E-02
0.6	32	8.26E-03	0.6	32	4.64E-02	0.6	31	5.01E-02	0.6	31	9.15E-02
0.7	41	1.07E-06	0.7	39	8.38E-04	0.7	38	8.04E-04	0.7	37	1.88E-03
0.8	34	1.91E-06	0.8	27	6.18E-04	0.8	28	7.16E-04	0.8	27	3.03E-03
0.9	29	9.98E-05	0.9	23	6.99E-04	0.9	20	1.04E-03	0.9	21	8.23E-03
1	25	1.80E-01	1	22	5.62E-03	1	22	1.17E-02	1	21	1.79E-02
1.1	14	5.47E-04	1.1	11	3.50E-03	1.1	12	1.42E-03	1.1	11	2.92E-03
1.2	15	9.12E-04	1.2	20	6.43E-03	1.2	14	3.01E-02	1.2	20	4.20E-02
1.3	14	9.37E-02	1.3	13	7.52E-02	1.3	12	1.35E-01	1.3	11	1.19E-01
1.4	11	7.43E-04	1.4	12	8.21E-02	1.4	11	1.66E-01	1.4	10	1.20E-01
1.5	6	6.23E-03	1.5	9	4.06E-02	1.5	7	1.80E-02	1.5	9	1.60E-01
1.6	10	4.73E-01	1.6	11	9.73E-02	1.6	12	1.74E-01	1.6	11	1.14E-01
1.7	5	3.37E-02	1.7	6	1.78E-01	1.7	5	1.90E-01	1.7	6	2.19E-01
1.8	5	4.08E-02	1.8	8	1.24E-01	1.8	7	1.52E-01	1.8	8	1.34E-01
1.9	2	6.87E-01	1.9	3	2.86E-01	1.9	3	2.03E-01	1.9	3	3.26E-01
2	5	1.72E-01	2	7	1.72E-01	2	7	3.35E-01	2	7	2.74E-01
2.1	3	7.95E-01	2.1	4	2.07E-01	2.1	4	3.55E-01	2.1	4	2.36E-01
2.2	6	5.15E-01	2.2	8	3.72E-01	2.2	8	3.63E-01	2.2	8	4.14E-01
2.3	3	1.96E-01	2.3	3	2.16E-01	2.3	3	3.00E-01	2.3	3	2.47E-01
2.4	2	7.30E-01	2.4	3	2.40E-01	2.4	3	2.79E-01	2.4	3	2.31E-01
2.5	2	5.87E-01	2.5	2	1.05E-01	2.5	2	2.00E-01	2.5	2	1.57E-01
2.7	1	NaN	2.6	1	NaN	2.6	1	NaN	2.6	1	NaN
2.8	3	6.63E-01	2.7	2	5.00E-01	2.7	2	5.00E-01	2.7	2	5.00E-01
3.3	2	7.05E-01	2.8	4	2.11E-01	2.8	4	3.22E-01	2.8	5	3.00E-01
3.5	1	NaN	3	1	NaN	3	1	NaN	3	1	NaN
4.3	1	NaN	3.3	2	2.06E-01	3.3	2	3.24E-01	3.3	2	2.26E-01
6.2	1	NaN	3.4	1	NaN	3.4	1	NaN	3.4	1	NaN
-	-	-	3.5	1	NaN	3.5	1	NaN	3.5	1	NaN
-	-	-	4.3	1	NaN	4.3	1	NaN	3.8	1	NaN
-	-	-	6.2	1	NaN	6.2	1	NaN	4.3	1	NaN
-	-	-	-	-	-	-	-	-	6.2	1	NaN

Table B-4 - P-values of three addtional Iowa soils from the Scenario 2 rainfall analysis in Section 3.4.2

Silty Clay			Loamy Sand			Clay Loam		
Daily Precip (in.)	Count	P-value	Daily Precip (in.)	Count	P-value	Daily Precip (in.)	Count	P-value
0.1	255	1.00E+00	0.1	222	1	0.1	324	1.00E+00
0.2	112	6.82E-01	0.2	89	1.00E+00	0.2	132	7.25E-01
0.3	77	1.29E-01	0.3	64	9.54E-01	0.3	87	1.91E-01
0.4	52	8.93E-04	0.4	49	5.04E-01	0.4	63	2.91E-04
0.5	33	1.47E-02	0.5	34	2.01E-01	0.5	41	1.15E-02
0.6	34	1.53E-01	0.6	29	2.80E-01	0.6	37	8.75E-02
0.7	37	5.25E-04	0.7	38	2.64E-01	0.7	42	2.18E-03
0.8	28	1.98E-03	0.8	25	1.91E-03	0.8	31	1.36E-04
0.9	24	6.99E-04	0.9	21	1.33E-02	0.9	23	1.11E-03
1	22	1.73E-02	1	21	7.33E-03	1	22	4.19E-03
1.1	16	8.75E-03	1.1	11	1.55E-01	1.1	13	2.81E-03
1.2	20	3.69E-03	1.2	13	4.74E-02	1.2	22	4.39E-03
1.3	14	7.47E-02	1.3	12	2.56E-01	1.3	13	4.65E-02
1.4	13	5.80E-02	1.4	10	8.83E-02	1.4	12	9.92E-02
1.5	10	9.24E-02	1.5	6	4.29E-02	1.5	8	5.13E-02
1.6	13	1.26E-01	1.6	8	2.07E-01	1.6	12	9.83E-02
1.7	6	1.76E-01	1.7	5	6.09E-01	1.7	6	1.84E-01
1.8	8	1.82E-01	1.8	5	6.55E-02	1.8	8	8.32E-02
1.9	3	2.90E-01	1.9	2	2.74E-01	1.9	3	3.26E-01
2	7	2.15E-01	2	7	3.17E-01	2	7	1.39E-01
2.1	4	1.87E-01	2.1	3	1.03E-01	2.1	4	1.64E-01
2.2	9	3.81E-01	2.2	6	1.82E-01	2.2	8	2.84E-01
2.3	3	3.27E-01	2.3	3	1.91E-01	2.3	3	2.19E-01
2.4	4	3.37E-01	2.4	3	1.48E-01	2.4	3	2.66E-01
2.5	2	6.08E-02	2.5	2	2.86E-01	2.5	2	1.25E-01
2.6	1	NaN	2.6	1	NaN	2.6	1	NaN
2.7	2	4.49E-01	2.8	3	7.47E-02	2.7	2	3.70E-01
2.8	5	1.98E-01	3.3	2	2.03E-01	2.8	4	1.90E-01
3	1	NaN	3.5	1	NaN	3	1	NaN
3.3	2	1.77E-01	6.2	1	NaN	3.3	2	2.45E-01
3.4	1	NaN	-	-	-	3.4	1	NaN
3.5	1	NaN	-	-	-	3.5	1	NaN
3.8	1	NaN	-	-	-	4.3	1	NaN
4.3	1	NaN	-	-	-	6.2	1	NaN
6.2	1	NaN	-	-	-	-	-	-

APPENDIX C: MATLAB CODE FOR SIMPLIFIED CATCHMENT SCALE MODEL

```
clc
clear


DHourlyDates = DateMat(1981,1,1,2010,12,31);              % Creates complete hourly date matrix that is to
be filled with the drained field flow data
UDHourlyDates = DateMat(1981,1,1,2010,12,31);             % Creates complete hourly date matrix that is to
be filled with the undrained field flow data

Dates = datevec(DHourlyDates(:,1));
% This loop reads in all the DRAINMOD results for the different drained
% scenarios into one file called DHourlyDates to be used later in the
% convolution.
for cc = 1:6;

Dfiles = {'ClayLoam.SRO','SandyLoam.SRO','Loam.SRO','LoamySand.SRO','SiltLoam.SRO','SiltyClayLoam.SRO'};
% These are the DRAINMOD results files which are in units 0.01 mm but get converted to mm by DMODHourConv.
% Do not trust the DRAINMOD Manual it says the units are 0.01 inches.  NOT TRUE!!!
% This file order is also the scenario order used in the convolution equation: ClayLoam.SRO = 1,
FineSandyLoam.SRO =2, etc.

Drainflowdata = DMODHourConv(char(Dfiles(cc)));          % Converts DRAINMODs hourly outputs to a format
usable in Matlab

% Matching DRAINMOD Results to a Complete Hourly Date Matrix

 c = length(Drainflowdata(:,1));                         % This gives the length of columns which is
necessary for giving the correct linear index of the flow value in the next steps
 [tf,loc] = ismember(Drainflowdata,DHourlyDates(:,1));   % This function outputs the linear index of the
Hourly Dates that match the dates of the DRAINMOD flow values

for m = 1:numel(Drainflowdata);                          % This loop matches the appropriate flow value for
each date and inserts it into the hourly dates matrix
    if loc(m)>0;
        DHourlyDates(loc(m),cc+1)=Drainflowdata(m+c);    % The m+c gives the linear index of the flow value
matching the correct date.
```

```
    else
    end
end
end

% This loop reads in all the DRAINMOD results for the different undrained
% scenarios into one file called UDHourlyDates to be used later in the
% convolution.
for cc = 1:6;

UDfiles =
{'ClayLoamud.SRO','SandyLoamud.SRO','Loamud.SRO','LoamySandud.SRO','SiltLoamud.SRO','SiClLoud.SRO'};
% These are the DRAINMOD results files which are in units 0.01 mm but get converted to mm by DMODHourConv.
% Do not trust the DRAINMOD Manual it says the units are 0.01 inches.  NOT TRUE!!!
% This file order is also the scenario order used in the convolution
% equation: ClayLoamud.SRO = 1, FineSandyLoamud.SRO =2, etc.

UDflowdata = DMODHourConv(char(UDfiles(cc)));          % Converts DRAINMODs hourly outputs to a format
usable in Matlab

% Matching DRAINMOD Results to a Complete Hourly Date Matrix

 c = length(UDflowdata(:,1));                          % This gives the length of columns which is
necessary for giving the correct linear index of the flow value in the next steps
 [tf,loc] = ismember(UDflowdata,UDHourlyDates(:,1));   % This function outputs the linear index of the
Hourly Dates that match the dates of the DRAINMOD flow values


for m = 1:numel(UDflowdata);                           % This loop matches selects the appropriate flow
value for each date and inserts it into the hourly dates matrix
    if loc(m)>0;
        UDHourlyDates(loc(m),cc+1)=UDflowdata(m+c);    % The m+c gives the linear index of the flow value
matching the correct date.
    else
    end
end
```

```
end



% Adding Monthly Lateral Seepage data to the hourly DRAINMOD outputs
DrainedLS = xlsread('FinalLateralSeepageNumbers.xlsx',1);   % Reads the monthly seepage values gathered
from DMOD drained outputs
UndrainedLS = xlsread('FinalLateralSeepageNumbers.xlsx',2); % Reads the monthly seepage values gathered
from DMOD undrained outputs

% Adding seepage to the drained data

k=1;                     % Sets the counter
for i = 1981:2010;       % Year
for j = 1:12;            % Month
if j >=1 && j<=11;       % A different scenario is necessary for month 12 in terms of the counter
D1 = datenum(i,j,1);     % Sets the beginning of the month datenumber
D2 = datenum(i,j+1,1);  % Sets the end of the month datenumber
Selector = DHourlyDates(:,1)>D1 & DHourlyDates(:,1) <= D2;  % Creates logical vector of the hourly dates in
the month
days = round(sum(Selector)/24);  % Determines the number of days in that month
for l = 1:6;                     % Sets the number of scenarios for the loop that the lateral seepage
values are added to
DHourlyDates(Selector,l+1) = DHourlyDates(Selector,l+1)+DrainedLS(k,l+2)*10/days/24;  % Adds the monthly
average hourly seepage value to the overall hourly waterloss values
end
k=k+1;
else
D1 = datenum(i,j,1);  % This is for month 12 because it needs to have month 1 as its end date and not 13.
D2 = datenum(i+1,1,1);
Selector = DHourlyDates(:,1)>D1 & DHourlyDates(:,1) <= D2;
days = round(sum(Selector)/24);
for l = 1:6;
DHourlyDates(Selector,l+1) = DHourlyDates(Selector,l+1)+DrainedLS(k,l+2)*10/days/24;
end
k=k+1;
end
```

```
end
end


% Adding seepage to the undrained data

k=1;
for i = 1981:2010;
for j = 1:12;
if j >=1 && j<=11;
D1 = datenum(i,j,1);
D2 = datenum(i,j+1,1);
Selector = UDHourlyDates(:,1)>D1 & UDHourlyDates(:,1) <= D2;
days = round(sum(Selector)/24);
for l = 1:6;
UDHourlyDates(Selector,l+1) = UDHourlyDates(Selector,l+1)+UndrainedLS(k,l+2)*10/days/24;
end
k=k+1;
else
D1 = datenum(i,j,1);
D2 = datenum(i+1,1,1);
Selector = UDHourlyDates(:,1)>D1 & UDHourlyDates(:,1) <= D2;
days = round(sum(Selector)/24);
for l = 1:6;
UDHourlyDates(Selector,l+1) = UDHourlyDates(Selector,l+1)+UndrainedLS(k,l+2)*10/days/24;
end
k=k+1;
end
end
end

% Need to remove small negative flow values for simplicity of data analysis
negs = DHourlyDates<0;  % Logical test to find negative values
DHourlyDates(negs)=0;   % Sets negative values to 0
unegs = UDHourlyDates<0;
UDHourlyDates(unegs)=0;
```

```
% CAN START AT THIS POINT IF YOU LOAD THE RIGHT MATRICES

clc
clear
% Optimized Code for Convolution...booyah
load FinalCorrectDMODinputswLatSeep.mat  % This is the finished file that has the DRAINMOD outputs in the
correct format from the above steps

% topod = xlsread('Scenario1Correct.xlsx',1,'A2:H3750');     % This reads in the drained fields' topologic
data for the Original Scenario: Area and Link length are in km^2 and km
% topoud = xlsread('Scenario1Correct.xlsx',2,'A2:H2611');    % This reads in the undrained fields'
topologic data for the Original Scenario: Area and Link length are in km^2 and km
% topod = xlsread('Scenario1Correct.xlsx',3,'A2:H1394');     % This reads in the drained fields topologic
data for the Far Scenario: Area and Link length are in km^2 and km
% topoud = xlsread('Scenario1Correct.xlsx',4,'A2:H4967');    % This reads in the undrained fields topologic
data for the Far Scenario: Area and Link length are in km^2 and km
% topod = xlsread('Scenario1Correct.xlsx',5,'A2:H1277');     % This reads in the drained fields topologic
data for the Near Scenario: Area and Link length are in km^2 and km
% topoud = xlsread('Scenario1Correct.xlsx',6,'A2:H5084');    % This reads in the undrained fields topologic
data for the Near Scenario: Area and Link length are in km^2 and km
% topod = xlsread('Scenario1Correct.xlsx',7,'A2:H6360');     % This reads in the drained fields topologic
data for the All Drained Scenario: Area and Link length are in km^2 and km
topoud = xlsread('Scenario1Correct.xlsx',7,'A2:H6360');      % This reads in the drained fields topologic
data for the All Undrained Scenario: Area and Link length are in km^2 and km

% Drained Hydrograph
factsum(2:401)= rot90(cumsum(log(1:1:400)),3);          % This is used for the factorial term in the log
solution
times = zeros(100,1);                                   % Pre-allocates memory for time
times(:,1) = 1:100;                                     % Defines the time of the unit response constant;
40 hours is enough for all hillslopes to deliver all of their water to the outlet
Ohyd=zeros(length(DHourlyDates)+length(times)-1,1);     % Pre-allocates memory for the drained outlet
hydrograph
const = zeros(100,1);                                   % Pre-allocates memory for the constant matrix
v=0.81*3600;                                            % Velocity in m/hour
l=221;                                                  % Average reach length in m
                                                        % Starts timer
```

```
% This loop is for the Drained Scenarios
for j = 1:6                                                  % Loop 1 - J is the DRAINMOD Scenario Number
   sc = topod(:,8)==j;                                       % Finds the hillslopes corresponding to the DMOD
simulation j
   fields = topod(sc,6:7);                                   % Grabs the area and topologic distance of the
specified hillslopes
   const = zeros(100,1);
   for k = 1:length(fields)                                  % Loop 2 - k is each hillslope in the fields matrix
     d = fields(k,2);                                        % Topologic distance of k (links)
     a = fields(k,1)*1000^2;                                 % Area of k in m
     lnconst = -(v/l*times)+((d-1)*log((v/l*times)))-factsum(d);  % Natural log transormation of the
constant in the routing equation to avoid large numbers
     % const(:,k) = a*exp(lnconst);                               % Transformation back this version could
be used with parfor
     const = const+a*exp(lnconst);                                % This transforms the constant back and
sums it up over all the hillslopes of the DRAINMOD scenario
   end
    u = (v/l)*DHourlyDates(:,j+1)/1000;                                 % The appropriate DRAINMOD hourly
flow data converted to meters
    Ohyd = Ohyd+conv(u,const);                               % Convolution of DMOD sim j with the respective
constant response
end

AllDrainage=[DHourlyDates(:,1),((Ohyd(1:262968))/3600)/(.3048^3)];      % Creates a matrix of the catchment
hydrograph for the drained fields of the scenario



% Undrained Hydrograph
factsum(2:401)= rot90(cumsum(log(1:1:400)),3);           % This is used for the factorial term in the log
solution
times = zeros(100,1);                                     % Pre-allocates memory for time
times(:,1) = 1:100;                                       % Defines the time of the unit response constant;
40 hours is enough for all hillslopes to deliver all of their water to the outlet
Ohydu=zeros(length(DHourlyDates)+length(times)-1,1);     % Pre-allocates memory for the undrained outlet
hydrograph
const = zeros(100,1);                                     % Pre-allocates memory for the constant matrix
```

```
v=0.81*3600;                                                   % Velocity in m/hour
l=221;                                                         % Average reach length in m

for j = 1:6                                                   % Loop 1 - J is the DRAINMOD Scenario Number
   sc = topoud(:,8)==j;                                       % Finds the hillslopes corresponding to the
undrained DMOD simulation j
   fields = topoud(sc,6:7);                                   % Grabs the area and topologic distance of the
specified undrained hillslopes
   const = zeros(100,1);
   for k = 1:length(fields)                                   % Loop 2 - k is each hillslope in the fields matrix
     d = fields(k,2);                                         % Topologic distance of k (links)
     a = fields(k,1)*1000^2;                                  % Area of k in m
     lnconst = -(v/l*times)+((d-1)*log((v/l*times)))-factsum(d);  % Natural log transormation of the
constant in the routing equation to avoid large number errors in Matlab
     % const(:,k) = a*exp(lnconst);                             % Transformation back this version could be used
with parfor
     const = const+a*exp(lnconst);                              % This transforms the constant back and sums it up
over all the hillslopes of the DRAINMOD scenario
   end
    u = (v/l)*UDHourlyDates(:,j+1)/1000;                        % The appropriate DRAINMOD hourly flow data
converted from mm to meters
    Ohydu = Ohydu+conv(u,const);                                % Convolution of DMOD sim j with the respective
constant response (units of m^3/hour)
end

OrigDUDHG=[UDHourlyDates(:,1),((Ohydu(1:262968))/3600)/(.3048^3)];      % Creates a matrix of the catchment
hydrograph for the undrained fields of the scenario


OhydFinal = ((Ohyd+Ohydu)/3600)/(.3048^3);  % Converts the final hydrograph to cfs for comparison purposes
OrigDrainage = [DHourlyDates(:,1),OhydFinal(1:262968)]; % Creates the final overall catchment hydrographs
```

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