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Simulating the Hydrology in Poorly Drained Watersheds Using the SCS Curve Number and the Green & Ampt Methods

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Simulating the Hydrology in Poorly Drained Watersheds Using the SCS Curve Number and the Green & Ampt Methods

By

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ABSTRACT

Simulating the Hydrology and Water Quality in Poorly Drained Watersheds Using the SCS Curve Number and the Green & Ampt Methods

By

Lindsey Anne Dees

Two methods of simulating streamflow for a tile drained watershed were compared using the Soil and Water Assessment Tool (SWAT). The SCS curve number method (CN) was compared to the Green-Ampt Mein-Larson (GAML) method on the Vermillion River Watershed (VRW). The VRW is a 579 mi^2 watershed located in the "Tile Belt" of Central Illinois, and is a headwater stream to the Mississippi River Basin. The overall objective of this study was to determine if the SWAT model could adequately simulate the hydrology of an agricultural watershed with intensive subsurface drainage. The model was run on a daily basis during the period of 1970 – 1988 and model output under the two scenarios was compared to observed flow data. Both model approaches produced similar results with r^2 and Nash Sutcliffe efficiency values of 0.72 and 0.53, respectively. The analysis suggested that both methods worked equally well for the tile drained watershed and that while the watershed is drained, it still primarily acts from a water balance standpoint as a watershed with no subsurface drainage. For this example it was determined that modeling with more complex input data such as hourly rainfall is not necessary and that daily weather inputs can be used with equal results.

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To my Advisors…
Thank you for all that you have done to help me realize my goals.

To my Parents…
You are my greatest blessing, thank you for your unconditional love and support. Without you none of this would have been possible, I love you both.

To my Friends…
I cherish you all , thank you for the enduring laughter and happiness you have brought into my life.

and to Ryan…
You are my inspiration, thank you for believing in me.

Thank you everyone for supporting me, you have touched and enriched my life in so many ways.

~Lindsey

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KEY TO SYMBOLS

(1) Curve Number Equation

S	Potential maximum soil retention	in
CN	Curve number	

(2) Streamflow Flow

Q	flow	cm^3/s
S	Potential maximum soil retention	in
P	Total rainfall	in

(3) Darcy's Law

Q	flow	cm^3/s
A	Area	Acres
q	Specific discharge	m/s
dh/dl	Hydraulic gradient	
K	Hydraulic conductivity	m/s

(4) **Green-Ampt Infiltration Rate**

f_{infl}	Infiltration rate	mm/hr
K_e	Effective hydraulic conductivity	mm/hr
ψ_{wf}	Wetting front matrix potential	mm
$\Delta\theta_v$	Change in volumetric moisture content across wetting front	mm/mm
$F_{inf,t}$	Cumulative infiltration at time t	mm water

(5) **Hydraulic Conductivity Equation**

K_{sat}	Saturated hydraulic conductivity	mm/hr
CN	Curve number	

(6) **Calculation of Amount of Water Entering a Drain**

q_{tile}	Amount of water/lateral flow discharged to sub basin	mm
SW_{ly}	Soil water content of the layer at a given day	mm
t_{drain}	Time required to drain soil to field capacity	hrs
FC_{ly}	Field capacity of layer	
e	exponential	

(7) **Amount of Tile/Actual Flow Released to a Main Channel**

qtile	Amount of water/lateral flow discharged to sub basin	mm
q_t	Tile/lateral flow discharged to main channel	mm
$q_{tstor,\ i-1}$	Tile/lateral flow stored or lagged from pervious day	mm
$tile_{lag}$	Drain tile lag time	hr

(8) R-Squared Equation

r^2	Total variation in the measured data vs. the simulated data	
x	Simulated data	mm/hr or mm/day
y	Observed data	mm/hr or mm/day
$\bar{x}$	Average simulated	mm/hr or mm/day
$\bar{y}$	Average observed	mm/hr or mm/day

(9) Nash-Sutcliffe Equation

NS	Nash Sutcliffe	
O_i	Observed data	mm/hr or mm/day
P_i	Predicted data	
$\bar{O}$	Mean of observed data	mm/hr or mm/day

(10) Theiessen Polygon Method

$\bar{R}$	Average watershed rainfall	mm
W_i	Weighting factor	
R_i	i^{th} rainfall amount	mm

(11) Rational Method

Q_p	Peak flow rate	cfs
C	Dimensionless streamflow coefficent	
i	Rainfall intensity	in/hr

(12) Streamflow Coefficient

C	Dimensionless streamflow coefficent	
C_i		
A_i	Area	acres

(13) Streamflow Relationship

t_{tile}	Time it takes for discharge flow from tile to occur	hours
$t_{streamflow}$	Time it take for streamflow to occur	hours

1 INTRODUCTION

1.1 Background

Subsurface drainage (tile) systems are omnipresent across the Midwest. In 1985 it was estimated that 110 million acres of farm and rural areas were artificially drained in 22 states (Pavelis, 1987), with over 30% of tile drained cropland in the Great Lakes States alone (Hirschi, 2006). About half of these states, including Illinois, Indiana, and Iowa, make up the core of what has been deemed the "Cornbelt" or the "Tile Belt" regions. Much of the land in the Cornbelt was developed on former swamps and wetlands. A majority of the land in these areas is flat (slopes less than 2%), with poorly drained soils, and a high water table; without drainage the land would be too cold and wet for agricultural use (USDA, 2005). Tile drainage systems are implemented to reduce the risks associated with stagnant water in fields, improve soil structure, increase net income by allowing for earlier access during the growing season, and protect soils from uncontrolled runoff and erosion (Fausey et al., 1987). Although beneficial, these systems have potentially adverse effects on the water quality of the rivers, ditches, and streams that they discharge. Drained fields have also contributed to 87 % of recent wetland loss due to agricultural development (Thomas, 1987). Until recently, improving the production capacity of agricultural fields has been the primary focus of drainage research; however, due to the recent emphasis on water quality improvement and wetland mitigation through state legislature, the focus is now shifting to the chemical/nutrient transport that occurs via tile-drainage during flow events, and to preserving wetland resources.

In the northern Gulf of Mexico water quality has been a major concern for the past thirty years. Many of the watersheds in the Cornbelt states drain into the Upper Mississippi River Basin (UMRB), which feeds into the Gulf of Mexico. It has been demonstrated that nutrient and sediment loading from these resources contribute to the seasonal occurrence of low oxygen, or *hypoxia* in the Gulf (Slawecki et al., 2005). It has been estimated that the UMRB was the source of almost 39% of the nitrate load discharged into the Gulf between 1980 and 1996; 35% of this load has been attributed to tributary rivers of Iowa and Illinois alone (Goolsby et. al, 1999).

Tile-drainage is a major conduit for the movement of non-point source (NPS) pollutants. NPS pollutants are defined as pollutants carried by rainfall or snowmelt moving over and through the ground, such as erosion (Novonty et al., 1994). The sediment from erosion is also incorporated into streamflow, which is capable of carrying away pollutants and depositing them into lakes, rivers, wetlands, coastal waters, and under-ground sources of drinking water (EPA, 2000). These pollutants include:

- Excess fertilizers from agricultural lands and residential areas
- Salt from irrigation water
- Bacteria and nutrients from livestock operations
- Oil, grease and chemicals from urban streamflow

About half of the nitrogen in the Gulf comes from commercial fertilizers applied to the land in the UMRB, and 15% comes from livestock manure (Jha et al., 2004).

Other sources include urban runoff, industrial point sources and atmospheric deposition (Jha et al., 2004).

In 2000, the Environmental Protection Agency issued a National Water Quality Inventory Report. The EPA assessed 19% of the nations' total river and stream miles; 43% of its lake, pond, and reservoir acres; 36% of its estuarine square miles; and 92% of Great Lakes shoreline miles (EPA, 2000). They were able to conclude that agriculture is the leading source of NPS pollution in the surveyed rivers and lakes (EPA, 2000). Usage of nitrogen and phosphorous fertilizers is widespread in the agriculture industry, making it one of the greatest concerns in NPS pollution on our surface waters. On a fertilizer-year basis (July–June), farmers used about 12 million tons of N annually over the 2000–04 periods on their fields (Baumes, 2004).

In general, tile drains reduce surface runoff, erosion, and loss of phosphorus compared to fields that do not have altered subsurface flow. However, studies have shown that tile drainage systems increase nitrate (NO_3-N) losses from fields through movement of nitrate through the soil profile (Skaggs et. al. 1994; Baker, 1994). Nitrate loss through the tile-drained system can be high even when no fertilizer is applied (Baker and Johnson, 1997). Nitrate is very soluble; it leaches easily through the soil and into tile lines. Since subsurface drains are a major drainage mechanism in the Midwest, they are also a primary source for the nitrate found in streams and rivers (Cooke et al., 2002). Concentrations of nitrate in tile drains are usually quite high when compared to the EPA drinking water standard of 10 mg/l, often exceeding 40 mg/l (EPA, 2002).

Because of the unique hydrologic conditions that subsurface drains place on local hydrology it is difficult to determine the impact they have on the watershed scale from both a hydrologic and water quality standpoint. Studying these impacts on a watershed is typically time consuming and costly. It can take years to determine the effects that best management practices, weather, soils and tile drainage will have on such things as crop growth, stream flow and nutrient discharge. Tile drainage is particularly hard to examine because of the lack of information concerning its spatial distribution across a watershed and depth in the soil. These factors have lead to the development of hydrologic modeling and incorporation of geographical information systems (GIS) techniques. These methodologies make it possible to analyze watersheds in a timely and economically feasible manner. Many hydrologic models have the ability to estimate and predict hydrology and nutrient transport throughout a watershed.

In this study, the Soil and Water Assessment Tool (SWAT) (Arnold et al., 2005) was evaluated for its suitability to simulate the hydrology of a Midwestern agricultural watershed with significant subsurface drainage. The model was to assist water resources managers in predicting and assessing the impact of management on water, sediment and agricultural chemical yields in large, un-gaged watersheds. The model is a process-based, continuous model capable of simulating many years of a hydrologic period and operates on a daily time step. The model was evaluated for its ability to accurately predict the tile flow in the Vermillion River Watershed in East Central Illinois.

This study focused on the Vermillion River Watershed in Illinois. This watershed is representative of many tiled watersheds in the Cornbelt region. Its rivers receive input from tile-drained watersheds that are predominantly agricultural in landscape and land usage. It was also chosen on the basis of climate, rainfall, and landscape data availability. Although only one watershed was investigated, the methodology and results can be applied to title-drained watersheds throughout the Midwest.

The Vermillion River Watershed encompasses 579 mi^2; however, assumptions can be made for larger or smaller watersheds, or watersheds with varying parameters such as land usage or climate. This study will evaluate the ability of the model to accurately estimate the stream flow for the watershed over the 24 year time period.

1.2 Objectives

The overall objective of this study was to evaluate the ability of the SWAT model to accurately simulate the hydrology of a Midwestern agricultural watershed with significant subsurface drainage.

Specific Objective

1. Evaluate and compare the different water balance models within SWAT using both daily and hourly precipitation inputs.

2 LITERATURE REVIEW

2.1 Tile Drainage

Tile drainage is a major factor in Midwestern agriculture. The drains allow for land that was once too wet to become productive. However, it also contributes to a greater volume of flow to downstream water bodies. This can increase nitrate and other nutrient movement to the groundwater or surface water bodies because of the shortened leaching period and rapid infiltration rate. Tile drainage also has had a negative effect on wetland resources. The rich soils within Midwestern wetlands have been drained and converted to cropland.

Tile drainage poses a problem in determining the amount of nutrient carrying streamflow that could occur within a watershed. Most watershed scale hydrologic approaches do not incorporate the tile-drainage component to the landscape and are not accurately estimating the amount of discharge into the lakes and streams (Cooke et al., 1999).

We have little knowledge of the depth and spacing of tile drains in older agricultural fields. Many older systems were originally designed for the sole purpose of quickly removing excess water from the plant root zone to prevent wet stress and improve crop yields, and location and depth were haphazard (Fausey, 1987, and Cooke et al., 1999) this lack of information is exacerbated on the watershed scale. At least in the State of Illinois, the Illinois Drainage Guide can be used as a rough estimate of spacing and depth based on specific soil types that have been traditionally drained. This knowledge can be beneficial when trying to model the streamflow and subsurface drainage from a field and or watershed.

2.2 Drainage Best Management Practices

Best Management Practices (Bump's) are often the most common control and prevention methods for NPS pollution from agriculture. These methods can be applied to practices such as tillage, and evaluated over time to see if it yields an outcome more compatible with water quality goals. The evaluation and assessment of the impact of the BMP's can be accomplished with two general approaches: (1) by collecting field data over an extended time period or; (2) Using computer simulation models developed from current scientific knowledge (Ahmad et al., 2002).

In recent years a number of different BMP's to reduce nitrate loads from subsurface drainage have been developed and tested at the plot and field scale. Recently, shallow tile-drainage has been used as a management practice for reducing the amount of nitrates discharged into the lakes and streams. In the winter and early spring water tables tend to be higher, which allows for a larger anaerobic zone that promotes denitrification of excess nitrate below the tile drains (Cooke et al., 1999). The nitrate that would normally be leached through deep tiles will be converted to gas and released into the atmosphere. This is a less expensive alternative to nitrate removal via secondary treatment.

Streamflow from tile-drainage is also impacted by the different tillage practices applied directly to the soils. Tillage practices directly affect the soil water properties of the surface soil and in turn the soil leaching characteristics (Kanwar et al., 1988). Tillage practices can also influence the distribution and continuity of macro pores that can act as preferential pathways for rapid movement of water and chemicals to the groundwater (Singh et al., 1991).

2.3 Wetlands-Overview

Wetlands are an integral part of the terrestrial ecosystem. Defined as "*lands that are seasonally or permanently covered by shallow water, as well as lands where the water table is closer to or at the surface*" (Environment Canada, 2002), they help regulate stream flow, remove nutrients and contaminants through plant uptake, reduce flooding, and help to settle sediments from upstream erosion. They also provide habitat for diverse wildlife, nesting grounds for birds, and breeding sanctuaries for fish. They are essential to maintaining water quality in the Midwest and other parts of the globe (Environment Canada, 2002). All of these factors boast a high economical value; however for landowners they can have a negative commercial effect. Many wetland owners are not compensated for the maintenance and repair of a wetland. The result of this is that dry, productive land is seen as a higher economic value (Environment Canada, 2002), which can be achieved by drainage.

2.4 History of Land Drainage

The importance of land drainage for economic and health reasons has been an issue in the United States since the nineteenth century when congress enacted the Swamp Land Acts in 1849 and 1850. These were the first important legislature developed concerning land drainage (Beauchamp, 1987). These Acts granted 64 million acres of swampy wetlands to Louisiana in 1849 and to 14 other States in 1850 and 1860 on the condition that proper drainage would be implemented and the land used as the States saw fit (Beauchamp, 1987).

Drainage is an important factor in eliminating diseases from crops, livestock, and humans. It helps eliminate stagnant water which serves as breeding grounds for mosquitoes and other parasitic organisms that transmit and cause disease (Beauchamp, 1987). It was also a major control strategy in fighting yellow fever and malaria, since land without stagnant water helps eliminate mosquito breeding grounds. Drainage also helps to eliminate mildew and root rot in plants, which can increase crop growth and production (Beauchamp, 1987).

The benefits of drainage can be immense; however the disposal of the drained water can be a significant concern to the environment and water quality. Agricultural drainage water often contains nutrients and chemicals that are harmful to humans and the environment (Hoffman et al., 1987). Drainage water often contains nitrate. Due to nitrate's negative charge, it is often repelled by the minerals in soil and readily leached into ground water systems, ending up in surface waters and streams (Hoffman et al., 1987). Groundwater accounts for 42% of the drinking water in the Unites States (Ward et al., 2005). Areas of high concern for nitrates in drinking water have been determined to be in close proximity to agricultural areas because of the well drained soils and use of fertilizer needed for crop growth (Manassaram et al., 2006). Nitrogen can deplete water of dissolved oxygen causing hypoxic conditions, and it has also been a contributing factor to methemoglobinemia (other wise known as blue baby syndrome), or the poisoning of the blood (Hoffman et al., 1987). Methemoglobinemia can occur when there are high levels of nitrate in a human body. Once ingested nitrate is reduced to nitrite which bonds to hemoglobin and forms methemoglobin; this disrupts the bloods capacity to carry oxygen. It is most common in infants because their bodies readily transform nitrate to nitrite; this process is slower in adults (Ward et al., 2005). Because of infant mortality associated with high nitrate levels, legislature has been written to limit the amount of nitrate (10 mg/l) that can be found in drinking water.

2.4.1 Nitrate Legislation

Over the past 20 years, substantial reductions have been achieved in the discharge of pollutants into the nation's air, lakes, rivers, wetlands, estuaries, coastal waters, and ground water. This has been done primarily by controlling point source pollution (EPA, 1995b).While such sources continue to be an environmental threat, the causes of impairment vary. Our waters may be threatened by urban, agricultural, or other forms of polluted streamflow; landscape modification; depleted or contaminated ground water; changes in flow; over harvesting of fish and other organisms; introduction of exotic species; bioaccumulation of toxics; and deposition or recycling of pollutants between air, land and water (EPA, 1995b).

The federal laws that address these problems have tended to focus on particular sources, pollutants, or water uses and have not resulted in an integrated environmental management approach; however they are a starting point to begin to improve nonpoint and point source pollution (EPA, 1995b).

Recognizing that unclean water is a threat not only to the environment but to public health as well, Congress enacted the Federal Water Pollution Control Act (FWPCA). Its main objective was to "*enhance the quality and value of our water resources and to establish a national policy for the prevention, control and abatement of water pollution.*"

In 1972 this law was amended, and since has been commonly called the Clean Water Act (EPA, 2003).

The Clean Water Act was established 1972 in order to reduce concentration of various toxic pollutants in the Great Lakes Region. Over the years, aspects of the Clean Water Act have changed. For example, Title I of the Great Lakes Critical Programs Act of 1990, put into place parts of the Great Lakes Water Quality Agreement of 1978. It was then that the USA and Canada agreed to reduce certain toxic pollutants in the Great Lakes. That law required EPA to establish water quality criteria for the Great Lakes addressing 29 toxic pollutants with maximum levels that are safe for humans, wildlife, and aquatic life (EPA, 2003).

The Clean Water Act was not as effective as the originators thought it would be. The different states involved did not provide consistent data useful for determining the water quality and effects of pollutants on the water. They were also unorganized in the respect of data collection and analysis. Each state had a different methodology for the procurement of such information, which does not allow for an accurate correlation for determining the source of pollutants (EPA, 2003).

In order to reduce the toxins, the Safe Drinking Water Act was established in 1974. This Act established limits on the concentration of certain drinking water contaminants allowed in public water supplies. These limits are set to protect human health and ensure that the water is of good quality (Stewart et al., 2001). The law requires EPA to determine safe levels of chemicals in drinking water which do or may cause health problems. These non-enforceable levels, based solely on possible health risks and exposure, are called Maximum Contaminant Level Goals.

2.4.2 Total Maximum Daily Loads

Each State has its own standard for the amount of a pollutant that a body of water can receive and still meet water quality standards (Brannan et al., 2005). These regulations were established based on section 303 (d) of the Clean Water Act, in order to reduce the amount of toxins in bodies of water. This is called the Total Maximum Daily Load (TMDL). The TMDL is the sum of the allowable loads of a single pollutant from all contributing point and non point sources (Brannan et al., 2005). The Clean Water Act requires States to evaluate and develop plans for their bodies of water to minimize their TMDL's. These plans must also incorporate solutions to better located and improve non-point and point source pollutions that are contributing to the contaminate levels.

The process of evaluating existing pollutant loads and their sources and developing proposals to reduce loads that are environmentally harmful and economically feasible to adjust is often difficult (Saleh, 2002). One of the difficulties in establishing TMDL's is the inadequacy of water quality monitoring data and lack of significant research pertaining to the sources of water quality impairment (Saleh, 2002). There is also a lack of information on the effectiveness of alternative management practices to reduce agricultural water pollution and the associated costs and benefits for different practice types (Saleh, 2002).

Each State contains its own TMDL's for the water bodies in its individual watersheds. In Central Illinois, the Vermilion River watershed currently contains fourteen waters that are not currently meeting EPA standards. Being predominantly agricultural, the highest risk is in the nutrients that are contained in the streamflow from the surrounding farms, followed by nitrates (>10mg/l), and phosphorus. The EPA recommends that total phosphorus concentrations should be less than 0.1 mg/l in rivers, and less than .05 mg/l where rivers enter lakes and reservoirs because concentrations higher could contribute to eurotrophication (EPA, 2000). On the list of priorities these watersheds are of a medium scale, they are not an immediate concern, but if left unattended could develop into a serious problem.

As industry and agriculture implement more technology into their working environment, pollution from NPS has become a more prevalent concern. Problems with chemical seepage into the ground water and streamflow into surface waters have led to violations of the Clean Water Act, Safe Drinking Water Act and many other regulations, especially from agricultural production systems. Impaired surface water quality from cropland erosion alone in 1995 resulted in $2-$8 billion in annual losses to recreational and commercial fishing, boating, municipal treatment plants, water storage facilities, and navigable waterways (Feather et al., 1995).

2.5 Models-Overview

Models are a useful tool in understanding the outcomes of agricultural implementations without the added cost or time of an actual scale project. Some field studies have been carried out for multiple years or seasons in order to reach a conclusion on which practice yields the best results. Hydrologic simulation models are now able to do this in a much shorter time period.

Models are generally classified as stochastic or deterministic. Stochastic models contain random variables, where deterministic models are free from variation (Chow et al., 1988). Deterministic hydrological models can be either lumped or distributed, and both are used to calculate the streamflow for single or continuous storm events (Chow et al., 1988). Lumped parameter models take into consideration the average values of the characteristics effecting streamflow, while distributed models divide the area into a number of elements and streamflow volumes are calculated separately for each element (Chow et al., 1988). All of these types of models are commonly used, and have been developed into many different components for various modeling needs.

Common continuous hydrologic models include: Hydrologic Simulation Program HSPF (Paul et al., 2002), Soil Water Assessment Tool or SWAT (Arnold et al., 2005), Chemical, Streamflow, and Erosion from Agricultural Management or CREAMS (Knisel, 1980), and Annualized Agricultural Non-point source Pollution Model or ANNAGNPS (Bingner et al., 2001).

Continuous models are able to analyze the effects of individual variables or changes on a watershed over an extended period of time. Variables include climate, topography, hydrological and land management practices. These types of models require an extensive period of time to calibrate and validate due to the large amount of data that is required for the simulation period, which may result in a less accurate simulation of the watershed response.

Commonly used single event based models include: Agricultural Nonpoint Source Pollution Model (Young et al., 1989), and Dynamic Watershed Simulation Model or DWSM (Borah et al., 2005). Single storm event models are needed for analyzing severe single-event storms and evaluating watershed management practices.

Commonly used field based models include: Drainage Model or DRAINMOD (Northcott et al., 2002), the Watershed Erosion Prediction Project or WEPP (Ascough et al., 1996), Ground Water Loading Effects on Agricultural Management Systems or GLEAMS (Morari et al., 1996), and the Root Zone Water Quality Model or RZWQM (Ma et al., 2000). Analysis using a field-based model only considers the area inside the watershed boundary. Many watershed scale models are developed from field scale models, many of which are derived from DRAINMOD, which is described along with SWAT and other continuous watershed scale models in the following sections.

2.6 Soil Water Assessment Tool

A deterministic continuous-time watershed scale model, SWAT was designed to assess the effect of long-term management decisions on un-gauged basins. SWAT simulates biomass production, plant growth, and evapotranspiration, and has the ability to deal with fertilization and management strategies on a daily time step (King et al., 1990).

The SWAT model has three main input parameters (1) Subbasins, (2) Reservoir Routing, and (3) Channel Routing. Eight major divisions make up the Subbasins parameter: hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, agricultural management, and pesticides (Spruill et al., 2000). Several of these parameters are described below, and were taken from the SWAT 2000 manual.

2.6.1 Weather

SWAT allows users to input observed data for precipitation, instead of letting the model generate the variables. One set of variables may be simulated for the entire basin, or different variables may be generated for each sub watershed (Neitsch et al., 2002).

Groundwater flow is modeled using shallow aquifer storage. The aquifer is recharges from percolation at the bottom of the root zone, and contributes directly to the stream flow (Neitsch et al., 2002).If snow is present, it may be melted on days when the second soil layer temperature exceeds 0 °C. Melted snow is treated the same as rainfall for estimating streamflow volume and percolation (Neitsch et al., 2002). There are three options for estimating potential evapotranspiration (ET): Hargreaves, Priestly-Taylor, and Penman Monteith (Neitsch et al., 2002).Channel losses are a function of channel width and length and flow duration. Both streamflow and peak rate are adjusted when transmission losses occur (Neitsch et al., 2002).

2.6.2 Hydrology

The watershed hydrology is represented using four basic storage volumes described by the following parameters: snow, soil profile (0 to 2 m), shallow aquifer (2 to 20 m), and deep aquifer (> 20 m) (Neitsch et al., 2002). The hydrology component is described by surface streamflow, percolation, lateral subsurface flow, groundwater, snow melt, evapotranspiration, transmission losses, and ponds. The surface streamflow volume for daily rainfall is predicted using the modified SCS curve number method (Neitsch et al., 2002).

Percolation is calculated as the water that drains through the root zone into the groundwater aquifer. The soil profile can be subdivided into multiple layers. SWAT utilizes a storage routing technique combined with a crack-flow model to predict percolation flow through each soil layer (Neitsch et al., 2002).

SWAT uses the lateral component as a basis for its tile drainage. This is an important factor in the modeling of tile-drained watersheds. It enables the user to specify parameters for the tile flow, depth, seepage time and lag time for the water to enter into the tile and then into the channel. A kinematic storage routing that is based on slope, slope length, and saturated conductivity is used to predict lateral flow in each soil layer (Neitsch et al., 2002).

The flood routing procedure uses a variable storage coefficient method. Flow rate and average velocity are calculated using Manning's equation, and travel time is computed by dividing channel length by velocity. Both streamflow and volume and peak rate are adjusted when transmission losses occur (Neitsch et al., 2002).

The SWAT model was developed by the USDA ARS to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large un-gauged basins (Liew et al., 2002). Either the SCS curve number method or the Green & Ampt infiltration model may be used to estimate surface runoff from precipitation. Adjustments to the curve number are made in the model to reflect changes that occur in simulated moisture conditions on the watershed (Liew et al., 2002) The other hydrologic processes that can be simulated by the model include evapotranspiration, infiltration, percolation losses, channel transmission losses, channel routing, and surface, lateral, shallow aquifer, and deep aquifer flow(Liew et al., 2002)

SWAT model was chosen for the following reasons:

1. The model is physically based; and simulates actual processes such as runoff, streamflow, tillage, and crop growth and tile-drainage.
2. The model supports the agricultural component.
3. There is a great level of model user support available.
4. Ease of parameter variability.
5. Very accessible for our use.

The Environmental Protection Agency (EPA, 2002) has listed limitations to the SWAT model, which include:

- It cannot be used for simulating sub-daily events such as a single storm event and diurnal changes of dissolved oxygen in a water body.
- Only for simulating conservative metal species from a point source.
- Cannot specify actual areas to apply fertilizer.
- Assumes one-dimensional well mixed streams and reservoirs.
- A large number watershed can be divided into hundreds of HRU's resulting in many hundreds of input files, which are difficult to manage and modify without a solid interface.
- The current version does not have a good model post-processor.

Though there are limitations, the model has proven to be accurate when modeling streamflow from watersheds. Because Swat met all of the criteria needed for this study, SWAT 2000 was chosen and it also incorporates an Arc View interface for the model input and output parameters.

2.6.1 DRAINMOD

The basis of most subsurface drainage models, DRAINMOD was developed in the late 1970's to simulate water table fluctuations and surface and subsurface drainage discharges for a variety of hydrologic and soils conditions, but has difficulty under frozen soil conditions (Sands, 2003; Mandramootoo, 1999). It can be used to compute daily, monthly or yearly outflows as a result of different tile drainage spacing (Kurien et al., 1997). It has become one of the most widely used subsurface drainage models around the world (Sands et al., 2003). The model is also used in predicting water table depth, evapotranspiration, and seepage on a day-to day and hour-to-hour basis (Helmers, 2004).

DRAINMOD uses the following components as inputs: Precipitation (hourly), Infiltration, the Green & Ampt equation, surface drainage, subsurface drainage, sub-irrigation, evapotranspiration, soil water distribution, and rooting depth.

DRAINMOD was originally developed strictly as a field scale model to aid in the design and analysis of subsurface drainage systems. More recent alterations of the field scale version of DRAINMOD have been developed for understanding the effects of land and water management practices on watersheds with poorly drained soils (Fernandez et al., 2004). These versions include DRAINMOD-DUFLOW, DRAINMOD-W, DRAINMOD-N, and DRAINMOD-GIS.

DRAINMOD-DUFLOW uses the St. Venant equation for one dimensional flow in open channels to determine watershed surface streamflow (Fernandez et al., 2004). DRAINMOD-W is a watershed scale model that is based on solution to the ADR equation, and interacts with stream hydraulics on a daily basis (Fernandez et al., 2004). DRAINMOD-N was developed to determine the fate and transport of nitrogen in subsurface drainage (Northcott et al., 2002). Perhaps the most commonly used version is the DRAINMOD-GIS. This model has the ability to generalize flow for areas where drainage is spatially distributed, and considers them as separate inputs instead of averaging them as a single entity (Fernandez et al., 2004).

DRAINMOD- GIS, though difficult to interface, has been successfully utilized in many studies on watersheds in the Midwest and in tile drained areas (Northcott et al., 2002, 2001, Singh et al. 2001). In a study done by Northcott et al. (2002) on the Upper Little Vermillion Watershed in east central Illinois, the model was tested for a five year period from 1993-1997. An r^2 value of 0.672 was obtained for the agreement between observed and estimated flows. In this study and in others it was found that DRAINMOD-GIS under predicted peak rainfall during dry years and over predicted in wet years (Singh, et al., 2001, Northcott, 2001).

Mandramootoo et al. (1999) conducted a study in Quebec on the Macdonald campus of McGill University. This site has well drained soils, with conventional drainage and sub irrigation. DRAINMOD-N describes the denitrification as a first order reaction, and it was found to overestimate the observed relationship between denitrification and the soil nitrate concentration by 60%. This was modified by replacing the existing equation with the Michaelis-Menten equation that accommodates both zero and first order reactions, and the relationship improved and had discrepancies as low as 23%.

A study using DRAINMOD on watersheds with tile drainage was carried out by Kurien et al. (1997) on four agricultural fields with Drummer/Flanagan soils in the Little Vermillion River Watershed, Illinois. Simulations were performed on this watershed for a 42 year period from 1951-1992. Drain spacing was varied from 10m to 300m using 10m increments while all other inputs were held constant. The results suggested that drain spacing was independent of location parameters, however when coupled with the hydraulic conductivity component, a 90% confidence interval for measured values was achieved.

DRAINMOD does not work well for steep slopes and other soil conditions. The model also lacks the ability to deal well with soil, nutrient, and pesticide loss components (Skaggs, W., 1980). DRAINMOD does not consider macro pore flow, or nitrate loss (DRAINMOD-N does) and does not have a plant growth component which could influence the streamflow on agricultural areas (Singh et al., 2001).

Limitations to DRAINMOD include the following:

1. DRAINMOD should not be applied to situations which are widely different than conditions for which it was developed, without further testing.

2. The field should have parallel subsurface drains.

For this study this model was not chosen due to lack of knowledge of the program and because of the unknown locations of the tile-drainage. It could be a potential problem if the fields did not contain parallel tile-drainage components. It also lacks the ability to simulate cold climate conditions, and while it has been modified to alleviate this problem, the successes of the modifications are questionable (Christopher et al., 2003).

2.6.2 Chemical, Streamflow, and Erosion from Agricultural Management Systems (CREAMS)

CREAMS is used to simulate the long term hydrologic effects of land management on an agricultural field (Spruill et al., 2000). It is applicable to field-sized areas, and is able to estimate streamflow using the SCS curve number method for daily rainfall data, and an infiltration based model for hourly data (Dunn, 1994).Though a good model, CREAMS has been found to be difficult to use (Dunn, 1994), and has led to the development of many other models. Several other models that are based on CREAMS include the Ground Water Loading Effects on Agricultural Management Systems (GLEAMS) model, the Simulator for Water Resources in Rural Basins (SWRRB) model, and the Erosion Productivity Impact Calculator (EPIC) (Ahmad et al., 2002).

2.6.3 Hydrologic Simulation Program (HSPF)

HSPF was developed to "simulate hydrologic and water quality processes in man-made water systems" (Spruill et al., 2000). The model has been applied all over North America and tested under numerous climates in countries around the world (Spruill et al., 2000). The model is a joint sponsorship between the EPA and U.S Geological Survey (USGS), developed to estimate the streamflow, sediment loads and pollutants in watersheds (Chou et al., 2003). Inputs for the model include: rainfall, temperature, sunlight intensity, land use, and soil properties, which are easily entered into the program, however the difficulty involved in calibrating the model for watersheds is a major drawback in choosing it for a study (Spruill et al., 2000).

2.6.4 AGNPS

The Agricultural Non-Point Source Pollution Model (AGNPS) has been used in the study of mildly sloped and tile-drained watersheds. This method was tested to determine if the SCS Curve number method could be used along with the model to depict flow from tile-drained watersheds (Walker et al., 2000). The model was validated and calibrated for two small (30 ha and 18 ha) watersheds in Piatt County Illinois (Walker et al., 2000). The study concluded that the AGNPS model needed further improvements to accurately simulate the conditions.

2.7 SWAT Surface Water Balance Structure

2.7.1 Curve Number Method

SWAT was designed to use the Green &Ampt equation and also use the Curve Number method for determining streamflow from watersheds. In the 1950's after 20 years of studies, the SCS (Soil Conservation Service) streamflow equation was developed (King et al., 1998). It is an empirical equation that determines streamflow based on daily soil moisture conditions. The equation is utilized in SWAT by comparing various land use and soil types in order to estimate total volume streamflow from small watersheds (King et al., 1998). It was developed using data from watersheds that were not predominantly tile drained, and had well-defined topography (Yuan et al., 2000). The curve number is the single parameter used in the method and can range from 35 to 98, where 35 represents a infinitely deep sand soil with no streamflow potential and 98 represents a surface where 100% of precipitation is converted to streamflow.

Curve numbers are assigned based on the combination of soil and landuse type. Soils are characterized by their soil hydrologic group. The Natural Resources Conservation Service (formerly SCS) has classified over 8,500 soils series into four hydrologic groups using their infiltration characteristics. The hydrologic groups have been designated A, B, C, and D. Group A is composed of soils considered to have a low streamflow potential. These soils have a high infiltration rate even when saturated. Group B soils have a moderate infiltration rate when saturated, and group C typically have a high streamflow volume (USDA, 1972). A table of curve numbers for different landuse and soil hydrologic group combinations under average conditions is available in (USDA, 1972).

The curve number is usually considered to be a model parameter for predicting surface runoff, but also includes subsurface flow (Walker et al., 2000). The method was developed to predict the initial or "quick" response of a watershed outlet to a storm event. In the case of tile-drained watersheds, total outlet response may be the sum of base flow or water flowing directly in through the sides and bottom of the ditch or stream channel, flow entering the ditch via field tile systems, and surface streamflow (Walker et al., 2000). Quick response may be predominantly tile-flow, with any surface streamflow being passed to the low lying areas of the watershed to exit as base flow or tile flow.

The curve number varies nonlinearly from dry conditions with soil water content at wilting point to wet conditions at field capacity, and finally approaches the maximum value at 100 percent saturation (Chu et al., 2004). The curve number technique relates surface runoff to land use, soil type, and management practices.

The following equation used by SWAT was evaluated for its applicability in tile-drained watersheds:

$$S = \left(\frac{1000}{CN}\right) - 10 \qquad (1)$$

Where:

S = Potential maximum soil retention in inches

CN = Curve Number

Curve Number values were obtained from Chapter 9 of the NEH-4 (National Engineering Handbook) for various land covers and soil textures.

Streamflow flow was descried by the equation:

$$Q = \frac{(P - 0.2S)^2}{(P + .8S)} \; for P > 0.2S \qquad (2)$$

Where:

Q = the direct flow volume expressed as a depth.

P = Total rainfall in inches.

Limitations of the SCS method are that the rainfall intensity and duration are not considered, only total rainfall volume. The method was developed for small, agricultural watersheds, which questions its credibility in watersheds that are very large. Another concern is that the SCS method was developed for warm weather conditions, and its accuracy is a concern for cooler conditions. As stated before, it was also empirically developed using data from areas with well defined topography. This makes estimating streamflow in areas with tile drainage difficult since there are many depressions and crevasses that go unaccounted for (Yuan et al., 2000).

The SCS curve number method is a widely used technique for determining an estimate of the amount of streamflow from a rainfall event. Though usually used for a single storm event, the method can be used to find an average annual streamflow value. This method is based on the area's hydrologic soil group, land use, treatment and hydrologic condition but does not differentiate surface flow from base flow (Walker et al, 2000).

SCS was designed to model surface runoff; however it has been the topic of many studies as to whether it can be applied to models that contain large amounts of tile-drainage.

Walker et al. (2000) conducted a study on the Little Vermillion River Watershed in East-Central Illinois. The study focused on using rainfall data from 1993 to investigate numerous aspects of the SCS Curve Number method in tile-drained watersheds including theoretical applicability of the method to modeling single-storm response in mildly-sloped and tile-drained watersheds, and the application of the results for predictive purposes. The study applied the method to the SWAT model and the AGNPS model. It was concluded that it was applicable in watersheds that are predominantly tile drained, however problems lie in assessing the wetness of the watershed prior to the rainfall event, which can skew the streamflow results.

2.7.2 Green & Ampt. Equation

SWAT uses the Green &Ampt equation, a physical- based model that was developed to predict infiltration by assuming water at the surface at all times (Green & Ampt, 1911). It is thought to better represent the impacts of land use on streamflow, because infiltration parameters can be directly related to catchments characteristics. However, such models require the rainfall data to be divided into constituent parts, which can be very difficult or impossible to obtain, even though the Green & Ampt equation has a physical basis, much may be lost or diluted by the regression equations needed to parameterize the model (King et al., 1998).

According to King et al. (1998) the major use and availability of the Green-Ampt method in agricultural hydrologic models has been limited to event-based models, and field-scale models. The availability of the Green-Ampt equation in a continuous-time scale model such as SWAT has been limited because of lack of research; however other models have utilized similar approaches. The Water Erosion Prediction Project (WEPP) model has a watershed version designed for simulating large basins (King et al., 1998). The Kinematic Streamflow and Erosion Model (KINEROS) uses a method called the Smith-Parlange infiltration model, which has been found to be very similar to the Green-Ampt (King et al., 1998).

Green Ampt is governed by Darcy's Law which relates the flux, the rate at which water moves through a unit cross sectional area with in the soil, to saturated hydraulic conductivity and the hydraulic gradient along the path of flow.

Darcy's Law

$$q = \frac{Q}{A} = -K\frac{dh}{dl} \tag{3}$$

Where:

q = Q/A is the specific discharge, dh/dl is the hydraulic gradient and K is the hydraulic conductivity.

The Green-Ampt infiltration rate is defined as

$$f_{inf,t} = K_e\left(1 + \frac{\psi_{wf} \cdot \Delta\theta_v}{F_{\inf,t}}\right) \tag{4}$$

Where:

$f_{inf,t}$ is the infiltration rate at time t (mm/hr), K_e is the effective hydraulic conductivity (mm/hr), Ψ_{wf} is the wetting front matric potential (mm), $\Delta\theta_v$ is the change in volumetric moisture content across the wetting front (mm/mm) and $F_{inf,t}$ is the cumulative infiltration at time *t* (mm water).

SWAT utilizes the equation to represent what happens as water infiltrates into the soil, the model assumes the soil above the wetting front is completely saturated and there is a sharp break in moisture content at the wetting front.

$$K_e = \frac{56.82 * K_{sat}^{.286}}{1 + 0.051 * \exp(0.062 * CN)} - 2 \tag{5}$$

Where:

K_e is the effective hydraulic conductivity, K_{sat} is the saturated hydraulic conductivity (mm/hr) and CN is the curve number. Since the effective hydraulic conductivity is inversely proportional to the curve number, the curve number parameter will have a large influence on the outcome.

2.7.3 Curve Number and Green Ampt Comparison

Both of the methods have been tested to determine which one provides the best results in a modeling perspective. It was concluded in a study of 585 storm events on 36 watersheds in six physiographic provinces of the central and Eastern U.S that the curve number was a good numeric index of land use (King et al., 1998). Additional studies by Wilcox et al. (1990) were carried out on six small catchments in Idaho, Arizona, Texas, Oklahoma, and Nebraska. The studies concluded that the Curve Number and the Green Ampt method gave similar results, and were both effective in predicting watershed streamflow.

For this study both of the parameters will be considered since the Green Ampt approach utilizes the Curve Number for its methodology in determining the streamflow rate for the watershed.

2.8 Validation of the SWAT Model

The SWAT model has been used on a range of watersheds in the United States, and has been thoroughly evaluated for accuracy. Srinivasan and Arnold (1994) compared monthly measured streamflow data and monthly simulated streamflow data from SWAT for a 20- month period for a large Texas watershed in the Seco Creek basin. They found that there were no tendencies to over or under predict surface runoff during seasons of the year for large watersheds. Their research conclusions reached an acceptable Nash-Sutcliffe r^2 value of 0.86.

Du et al. (2003) evaluated the SWAT model with modified tile drainage and pothole components at the watershed scale for nine years of observed flow and nitrate and nitrogen data for the large, flat, and poorly drained Walnut Creek watershed in Story County, Iowa. The model compared the SWAT 2000 version and the modified version (SWAT-M) for daily and monthly flow and nitrogen outputs. It was concluded that SWAT-M's simulated daily flows with less accuracy than monthly flows, and resulted in monthly Nash-Sutcliffe values that ranged from 0.69 to 0.79, and 0.09-0.18 for daily simulations.

The SWAT model was used by Spruill et al. (2000) to evaluate a small (5.5 km^2) central Kentucky watershed over a two-year period in 1995 and 1996. The model was found to adequately predict daily streamflow; however, it lagged the predicted peak and recession flows for the last half of 1995. The r^2 for monthly total flows in 1995 were found to be 0.58, and for 1996, 0.89. This study used a dye test to confirm that areas outside of the modeled watershed boundary do contribute to the streamflow, and calibration techniques were used to determine the parameters for channels into and outside of the watershed in order to determine streamflow. This study confirmed that SWAT is a good model to use on small watersheds when trying to predict monthly stream flow.

King et al. (1999) did a comparison study on SWAT's ability to use the Green-Ampt method and Curve Number method to predict streamflow for the Goodwin Creek Watershed in north central Mississippi. Rainfall data was modified for the Green-Ampt method to be evaluated on an hourly basis. Eight years of data were used in the study. Monthly model efficiencies were found to be 0.84 for the Curve Number method, and 0.69 for the Green & Ampt Method. The Curve Number method typically underestimated the surface streamflow, while Green & Ampt showed no trends. It was concluded that neither model was better than the other at predicting streamflow.

3 METHODS AND MATERIALS

Images in this thesis/dissertation are presented in color

3.1 Experimental Site and Observed Tile Flow Data

This study focused on the Vermillion River Watershed (VRW). This watershed was chosen based on its predominance of poorly drained soils and subsurface drains, percentage of agricultural land, soils data and availability of long term weather and observed streamflow data.

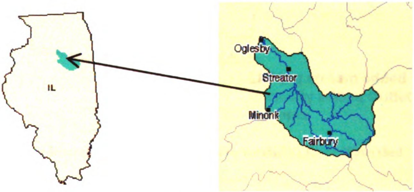

Figure 1:Location of the Vermilion River Watershed in Illinois
http://cfpub.epa.gov

3.2 Vermillion River Watershed Description

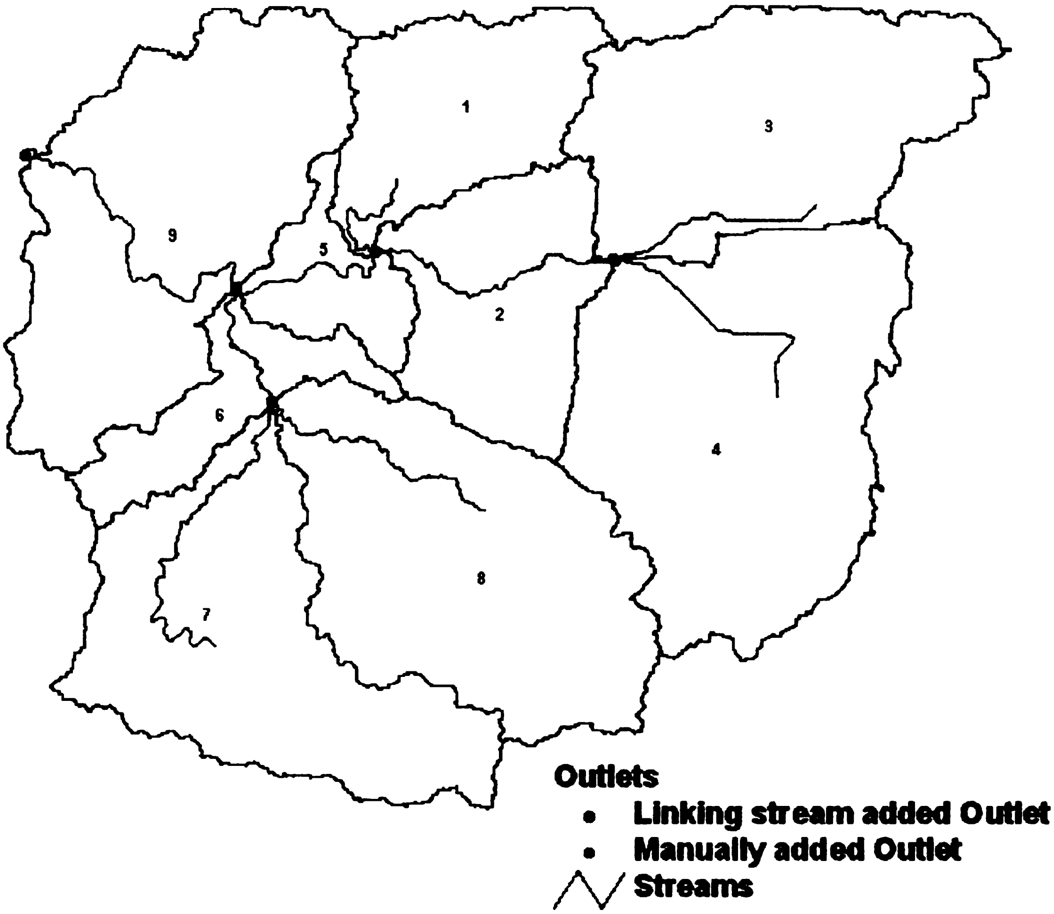

Figure 2: Discretization for 9 sub-basins in Vermillion River Watershed

The VRW (8-digit USGS Cataloging Unit 07130002) covers an area of 579 mi^2 and is situated in East-central Illinois within Ford, Iroquois, and Livingston counties. Like most of the rivers in east central Illinois, the Vermillion River is a tributary that directly drains into Illinois River, which is part of the Mississippi River Basin which discharges into the Gulf of Mexico. Because of the dominant agricultural landscape and its many tributaries, the Illinois River is a major carrier of sediment, streamflow, pollutants, and nutrients to the Mississippi River (Singh et al., 1991). The annual average precipitation over the basin for the years of this study (1970-1988) was approximately 960 mm. The watershed is comprised of ten different soil associations, mainly silty-clay and silt loams, which are illustrated be seen in Figure 3.

The soils of the VRW can be generally classified as Fil-silty, mixed, mesic, Typic Haplaquolls that are moderately permeable and poorly drained. These soils are representative of Central Illinois. They are typically found in the flat and low lying areas and can be very productive in dry years or when artificially drained, but can cause planting delays and/or flooding otherwise. Table 1 shows the distribution of soils within the watershed, their dominant texture and NRCS hydrologic soil group. The four Hydrologic Soils Groups are A, B, C and D as classified by the Natural Resource Conservation Service (NRCS). These are classified based on the soil's runoff potential, where A group soils tend to have the smallest runoff potential and D group soils the greatest.

Table 1: Soil mapping units for Vermillion River Watershed

Soil Mapping Unit	Common Name	Dominant Texture	NRCS Hydrologic Soil Group	Extent of Unit(Acres)	Total Area (%)
IL012	DRUMMER	Silty Clay	B/D	48072.5	13.2
IL014	SAYBROOK/DRUMMER	Silty Clay Loam	B/D	20149.0	5.5
IL016	ASHKUM	Silty Clay	B/D	72707.7	20.0
IL017	ANDRES	Silty Clay	C	67902.2	18.6
IL018	BRYCE	Silty Clay	D	80887.3	22.2
IL019	CLARENCE	Silty Clay Loam	D	10846.0	2.9
IL021	MILFORD	Silty Clay Loam	B/D	22632.1	6.2
IL022	WARSAW	Silty Clay Loam	B/D	7798.6	2.1
IL024	GILFORD	Sand	A	5318.2	1.4
IL081	ASHKUM/CHENOA	Silty Clay Loam	B/D	27129.8	7.4

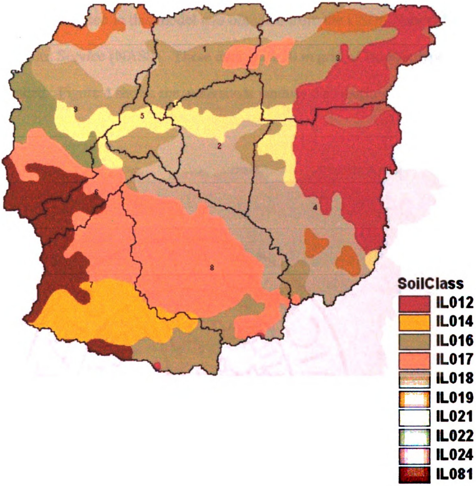

Figure 3: Distribution of soils in the Vermillion River Watershed

Almost 87% of the watershed is compromised of poorly drained soils that occur near the depression portion of the watershed landscape (Fehrenbacher et al., 1984). These soils are Ashkum, Bryce, Andres, and Drummer soils. Each of these soils is dark in color, made up of silty clay, and has slow permeability rates, especially in the substratum layer (Fehrenbacher et al., 1984).

3.2.2 Watershed Landuse

The landuse layer used in this model was obtained from the USDS National Agricultural Statistics Service (NASS). These data are a 30 m grid of landuse types across the watershed. Figure 4 shows the watersheds landuse distribution.

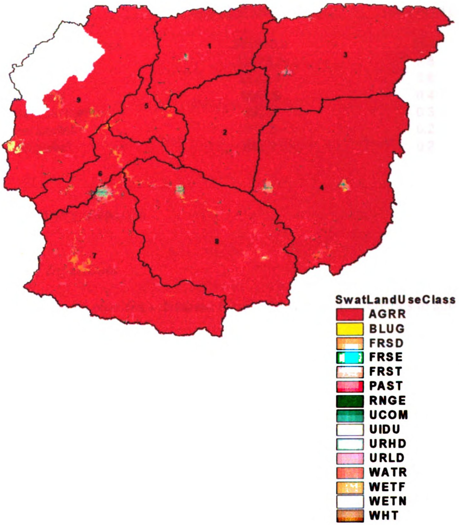

Figure 4: Landuse in the Vermillion River Watershed.

An analysis of the landuse layer indicates that the vast majority of landuse in the watershed is agricultural row crops nearly divided equally between corn and soybean shows a distribution of landuse across the watershed is given in Table 2.

Table 2: Landuse mapping units for Vermillion River Watershed

Landuse	Extent of Unit (Acres)	Total Area (%)
Agricultural Land-Row Crops	341830.0	94.0
Pasture	13875.7	3.8
Forest	2178.1	0.6
Wetlands	1549.9	0.4
Residential-Low Density	992.5	0.3
Water bodies	762.0	0.2
Industrial	641.2	0.2

3.3 SWAT MODEL INPUTS

3.3.1 Model Soil Input Data

The SWAT model requires a database of soil physical characteristics to simulate the hydrologic response of each soil. In this study a GIS layer of the State Soil Geographic Database (STATSGO) was used as an input layer into the SWAT model. For each STATSGO polygon, the SWAT model uses the dominant soil within the STATSGO polygon and accesses the STATSGO soils database for necessary soil parameters. The STATSGO database contains measured physical, chemical and biological parameters by delineated soil layer. Important soil parameters used in the SWAT water balance are bulk density, available soil water, and saturated hydraulic conductivity.

3.3.3 Model Climate Input Data

The SWAT model has the ability to use a number of different climate input parameters including rainfall, temperature, solar radiation, wind speed and relative humidity. With respect to precipitation data, SWAT can utilize rainfall data as either daily rainfall total or as hourly or sub-hourly rainfall data. SWAT users can also choose from two different types of rainfall-runoff models, the Curve Number Method or the Green- Ampt method. In this study the main objectives were to determine if there was a significant difference in watershed response between daily rainfall values versus hourly rainfall values, input types and also between runoff methods. To adequately test this, long term weather data is needed. Within the watershed there are three long-term National Weather Service climatological cooperative stations located at Piper City, Fairbury, and Pontiac. All three of these stations provide daily rainfall totals and maximum and minimum temperature data. Piper City also collects hourly and sub-hourly rainfall data. To model the watershed, daily and hourly weather data were collected from the National Climate Data Center (NCDC) for the period from 1970 -1988 (NCDC, 1970-1988).

3.3.4 Landuse Modeling Inputs

The vast majority of landuse of the watershed is row crop agriculture, primarily corn and soybean. To simplify the model runs, the entire watershed was represented as row crop agriculture. An initial study was performed to determine whether it was necessary to individually model both corn and soybean growth. Initial SWAT runs were made to determine if the watershed streamflow was different between a watershed modeled as corn versus a watershed modeled totally as soybean. This initial work showed that there was really no difference in the overall water balance between crops so the entire watershed was modeled as corn.

The corn crop was modeled in SWAT with operations that tried to closely replicate operational practices in the watershed. Crops were planted near mid April and harvested in mid September to early October. In order to simulate crop growth to its fullest potential, nitrogen and phosphorus fertilizers were supplied as the crop needed it so that they would not be a limiting factor to plant growth. A light tillage was performed every spring.

3.4 Subsurface Tile Flow

In SWAT, to simulate the tile flow the user must specify the depth from the soil surface to the drain, the amount of time required to drain the soil from saturation to field capacity, and the amount of lag between the time the water enters the tile until it exits the tile and enters the main channel (Ahamd et al., 2002). Tile drainage occurs when the soil water content exceeds field capacity in the soil layer where the tile drains are installed. The amount of water entering the drain on a given day is calculated with the equation

$$q_{tile} = (SW_{ly} - FC_{ly})(1 - e^{(-24/tdrain)}) \text{ if } \quad SW_{ly} > FC_{ly} \qquad (3.3)$$

Where:

q_{tile} is the amount of water (in mm) removed for the layer on any given day by the tile drainage, SW_{ly} is daily soil water content (in mm) of the layer on a given day,

FC_{ly} is the field capacity, and t_{drain} is the time (in hours) required to drain the soil to field capacity (Ahmad et al., 2002). SWAT treats all the water entering the channel as lateral flow.

In large sub-basins with a time of concentration greater than one day, only a portion of the tile/lateral flow will reach the main channel on the day that it is generated (Ahmad et al., 2002). SWAT incorporates a tile/lateral flow storage feature to lag a portion of the tile/lateral flow release to the main channel.

Once the tile/lateral flow is calculated, the amount of tile/lateral flow released to the main channel is calculated as

$$q_t = (q_{tile} + q_{stor,i-1})(1 - e^{-24/tilelag}) \qquad (3.4)$$

Where:

q_t is the amount of tile/lateral flow discharged to the main channel on a given day (mm), q_{tile} is the amount of tile/lateral flow generated in the sub-basin on a given day (mm), $q_{tstor,\ i-1}$ is the tile/lateral flow stored or lagged from the previous day (mm), and $tile_{lag}$ is the drain tile lag time (hr). Lagging the tile flow affects the timing (and thus the daily peaks) but not the total tile flow volume (Ahmad et al., 2002).

For this study, the model had to be calibrated for tile depth and spacing. To do this the Ddrain (depth of the subsurface drains), Tdrain(time to drain soil to field capacity in hours), and the Gdrain (drain tile lag time in hours) had to be determined. The average tile drainage depth in Illinois can range from 1-4 feet, so a set of parameters were determined to establish the most sensitive parameter.

3.5 Sensitivity Analysis

The method that was followed for the analysis of the input parameter sensitivity was proposed by Haan et al., (1995) and restated by Haan and Skaggs (2003). It is utilized by many researchers in this area, such as Feyereisen, Strickland, Bosch and Batten who used in it their research of sensitivity parameters in 2005 for the Little River Watershed in Georgia.

1. Determine objective functions of interest
2. Identify the most influential parameters
3. Perform a sensitivity analysis; select the most sensitive parameters for further study.

From the study conducted by Feyereisen et al., (2005) it was determined that watersheds that are predominantly crop land, such as the VRW, changing the curve number will significantly alter the amount of surface runoff. It was also determined that since crop lands contribute much of the moisture content to evapotranspiration, when an increase in curve number occurred the over all water yield was also increased.

3.6 Calibration and Evaluation Procedure

The ability of the model to estimate daily and monthly streamflow was tested using measured daily streamflow data obtained from the USGS gauging station at Pontiac, IL (Station07130002) from 1970 thru 1988. The model was then calibrated (the process of assigning specific values to the simulation model so that it accurately simulates runoff from a watershed) and validated (verify that the model has been properly calibrated by applying it to different sets of data than were used for the calibration). This model was validated using data from 1980 and 1981. This was done using the coefficient of determination (r^2), and the Nash-Sutcliffe model efficiency (NS).

The r^2 value represents how much of the total variation in the measured data is associated with the simulated data; it varies between 0 and 1, with a value of 1 indicating a perfect fit. Most statisticians consider a coefficient of determination of .7 or higher to be reasonable for a model.

$$r = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2 \sum(y-\bar{y})^2}} \quad (3.5)$$

Where:

x equals the simulated data and y equals the measured data.

The NS statistic indicated how close the plot of the simulated versus observed values correlate with each other, that is how close it is to a 1:1 ratio. The NS is calculated using:

$$NS = 1 - \frac{\sqrt{\sum_{i=1}^{N}(O_i - P_i)^2}}{\sqrt{\sum_{i=1}^{N}(O_i - \overline{O})^2}} \tag{3.6}$$

Where:

i and P_i are the observed and the predicted values, O is the mean of the observed values and *i* is the number of samples (hours). The NS can range from -∞ to 1, with 1 indicating a perfect fit.

It has been determined in a number of previous studies that the most sensitive parameter in the overall watershed water balance is the curve number. In most types of simulation models, the curve number is a static variable. The flexibility of the SWAT model allows multiple curve numbers in a given crop rotation to more accurately simulate the condition of the watershed. Two separate curve numbers were chosen to be calibrated for this study. The curve numbers were partitioned to represent the hydrologic conditions during a growing crop season and during the fallow season.

As a starting point in the model the initial curve numbers were chosen as 78 for the growing season and 86 for the fallow season. These choices were made based on NRCS recommendations for a row crop landuse grown on a B hydrologic soil group. The calibration procedure was performed holding one parameter (fallow season) constant while the growing season curve number was varied.

In the calibration and validation process a set of time series data were chosen as a calibration set to determine the best fitting parameters. To validate the model, those same parameters were applied to a second, independent set of data. In this study a two year time period (1980 – 1981) was chosen as the calibration data set because it represented average hydrologic conditions across the watershed. A portion of the time series was wetter than normal and another was dryer than normal. After the two curve numbers were calibrated for this time series they were applied to a second two year data set (1982 – 1983) to validate the model.

4 RESULTS AND DISSCUSSION

4.1 Vermillion River Watershed Daily Rainfall Results

The overall goal of this study was to determine if the SWAT model could be used to adequately simulate the hydrology of an agricultural field with intensive subsurface drainage. The model was evaluated with the curve number method using daily rainfall and with the Green-Ampt method using hourly rainfall data. In both cases, curve numbers for both the growing season and fallow season were calibrated. The model was run with a daily or hourly time step over the period 1970 through 1988. The model was calibrated for the two year period of 1980-1981, and validated over the two year period of 1982-1983 for both the daily and the hourly rainfall inputs.

There was not a significant difference between the predicted discharges for the daily rainfall data and the hourly rainfall data. Calibrated curve numbers for the daily data were 86 and 89 for growing season and fallow season respectively. The effectiveness of using the Curve Number method vs. the Green & Ampt method to predict surface streamflow throughout the watershed was also analyzed. The main focus of the study was to calibrate the daily and hourly rainfall data to coincide with the observed data with a well enough fit that the SWAT model could be used in place of long term field studies. The results for the daily and hourly rainfall data simulations were analyzed using the (R^2) and the Nash Sutcliffe values for the calibration and validation.

The curve number was found to be the most sensitive parameter in the SWAT model. For our evaluation the fallow season curve number along with the growing season curve number were calibrated with total monthly flow in 1980 and 1981. This was done for both the daily and hourly rainfall data by holding the growing season CN constant at a high value of 99, so that i could be optimized for the best r^2 value and then using that CN to optimize the growing season.

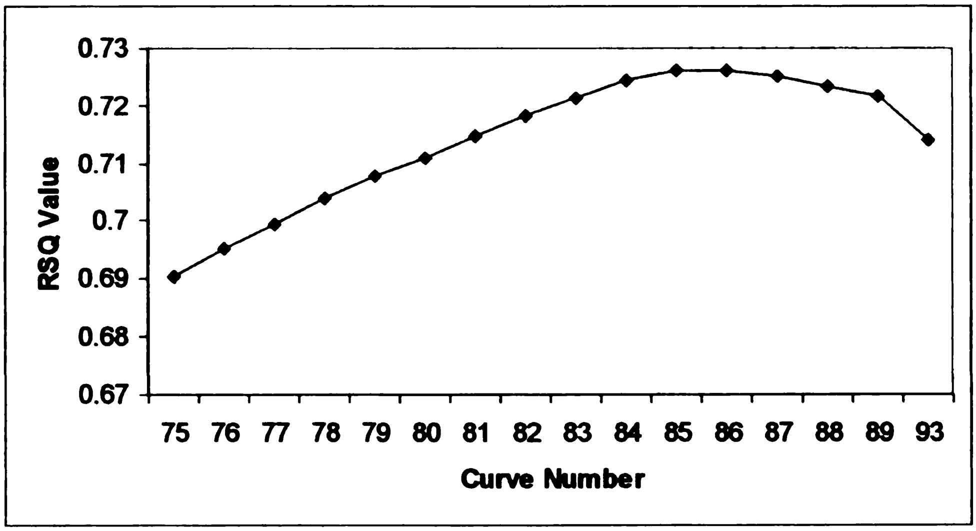

Figure 5: Curve Number and R^2 values for daily streamflow fallow season calibration time series CN methodology for two-year period 1980-1981

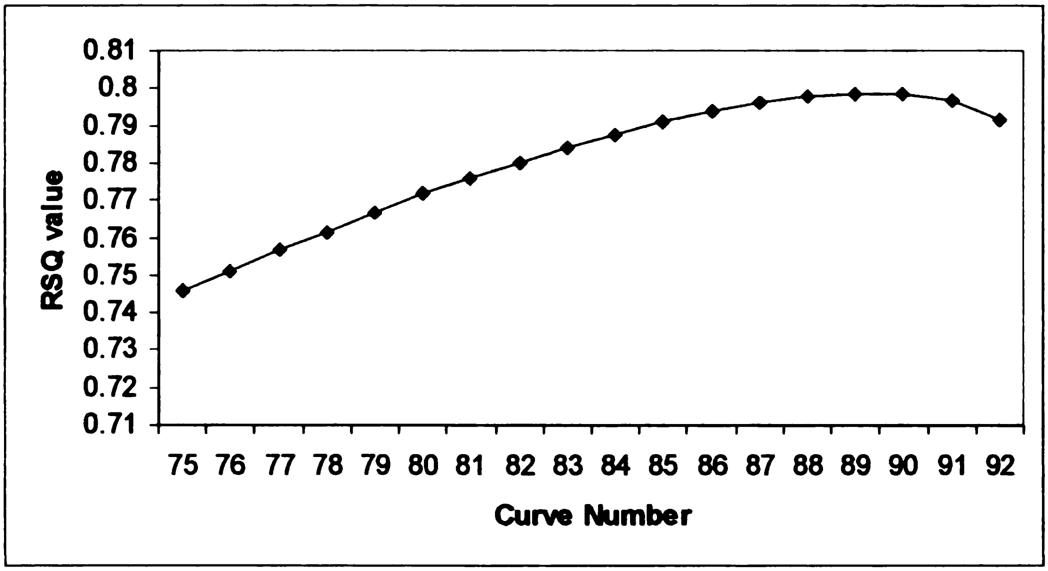

Figure 6: Curve number and R^2 values for daily streamflow growing season calibration time series CN methodology for two-year period for 1980-1981

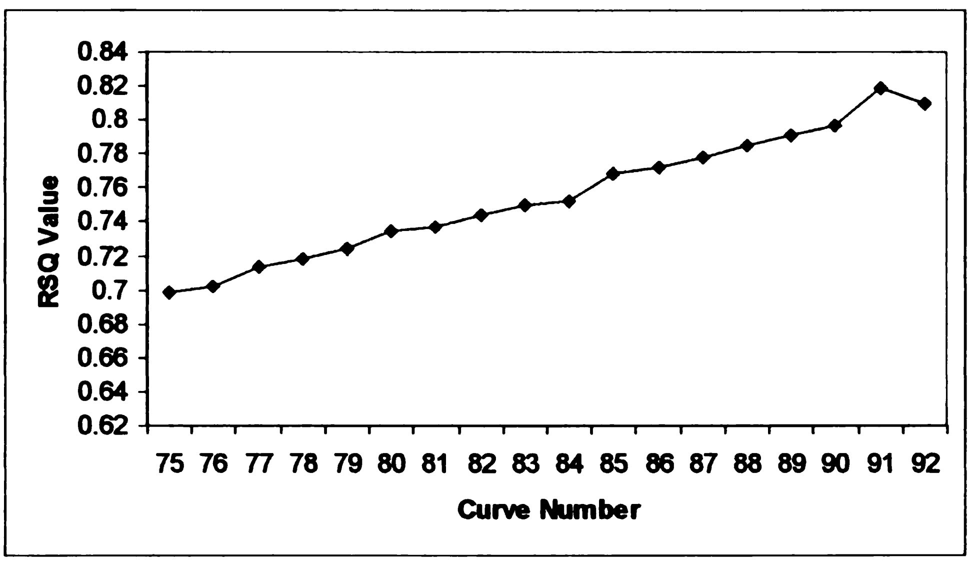

Figure 7:Curve number and R^2 values for hourly streamflow fallow season calibration time series GAML methodology for two-year period for 1980-1981.

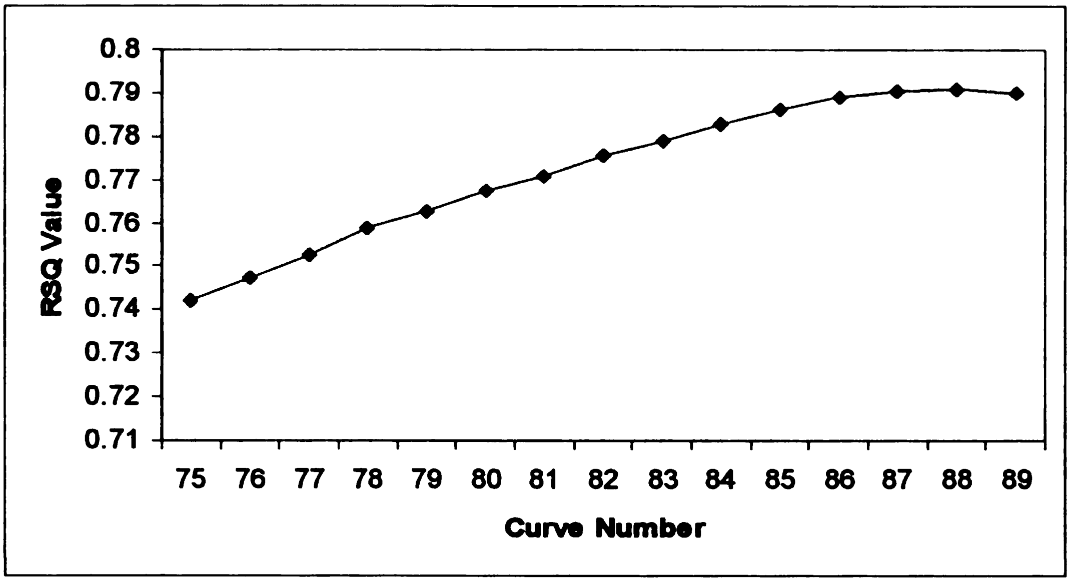

Figure 8: Curve number and R^2 values for hourly streamflow growing season calibration time series GAML methodology for two-year period for 1980-1981.

The model was calibrated for the GAML and CN using the years 1980 and 1981. An r^2 of 0.798 was determined for the monthly stream totals at the outlet of the VRW using the Curve Number method and daily rainfall values. Using the Green-Ampt method and hourly rainfall values the model was calibrated to an r^2 of 0.790.

In addition to the coefficient of determination, the Nash-Sutcliffe method was used to determine a goodness-of-fit (model efficiency) between the simulated and observed values for both runoff methods. The Nash-Sutcliffe method was chosen because it is more appropriate for time series data where the values of the data set are not independent of each other. It also does not have the bias that the coefficient of determination has for extreme values (i.e. high flood peak values). The values can range from negative infinity to 1. Values equal to one indicate a perfect fit between the observed and the simulated data. Values equal to or less than zero indicate that the simulated data are no better at representing the actual parameters than using the average of the observed data to predict the flow. Any value above zero suggests that the model has some integrity and can be used to represent the physical data to some extent.

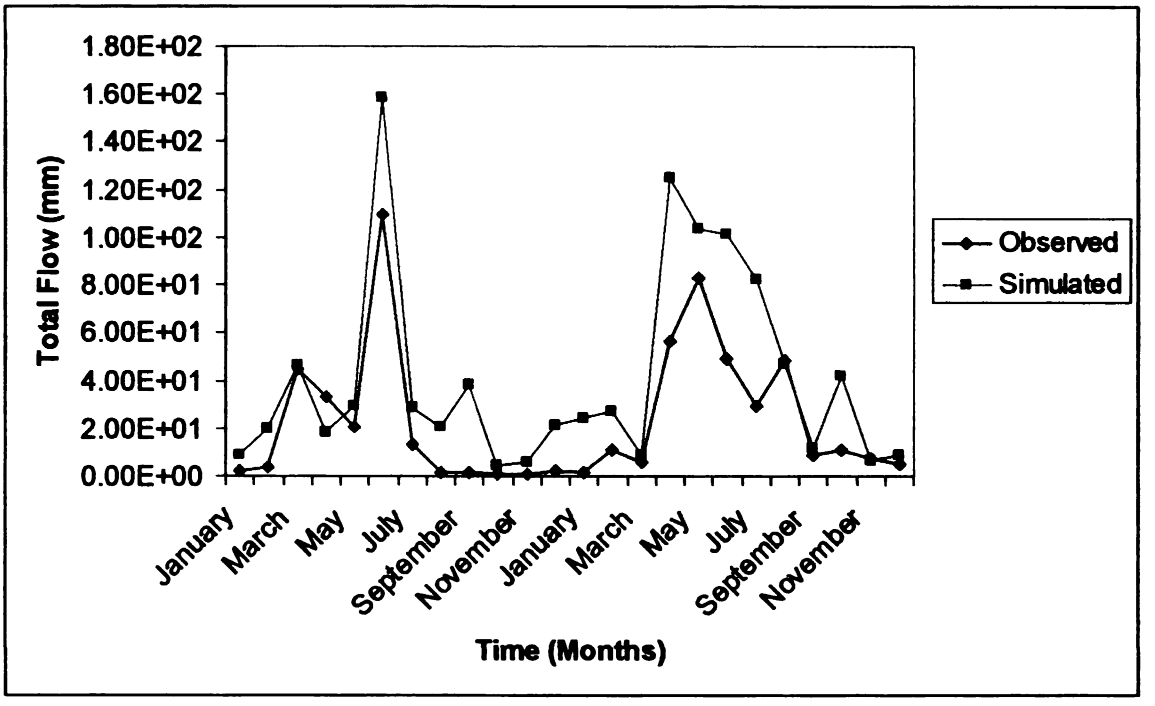

Figure 9: Observed and calibrated CN simulated monthly streamflow time series at outlet of VRW for two year time period from 1980-1981

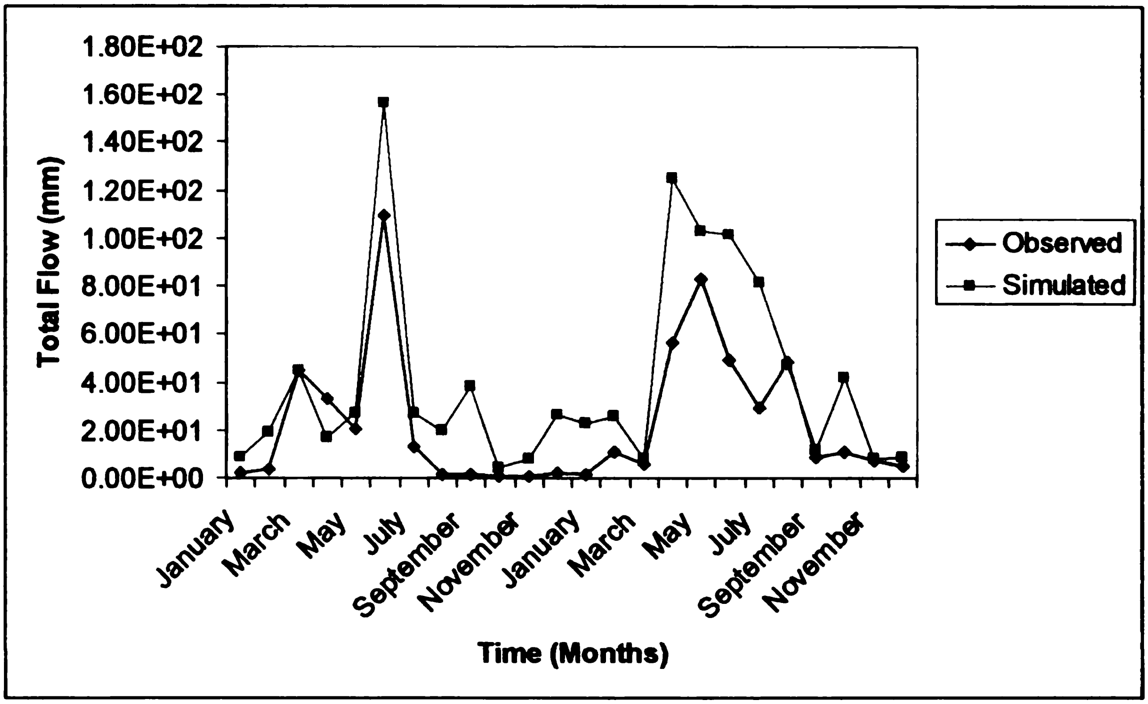

Figure 10: Observed and GAML simulated monthly streamflow time series at outlet of VRW for two year time period from 1980-1981

It can be seen from figures 9 and 10 that the simulated volumes are consistently greater than the observed methods for predicting the total monthly streamflow. To further evaluate the modeling approaches, the simulated results were compared to the observed data on a daily stream flow basis. Figures 12 and 13 shows the simulated and observed daily streamflow record during the calibration period. For this two year time period the r^2 and Nash-Sutcliffe efficiencies were 0.72, and 0.5367, respectively.

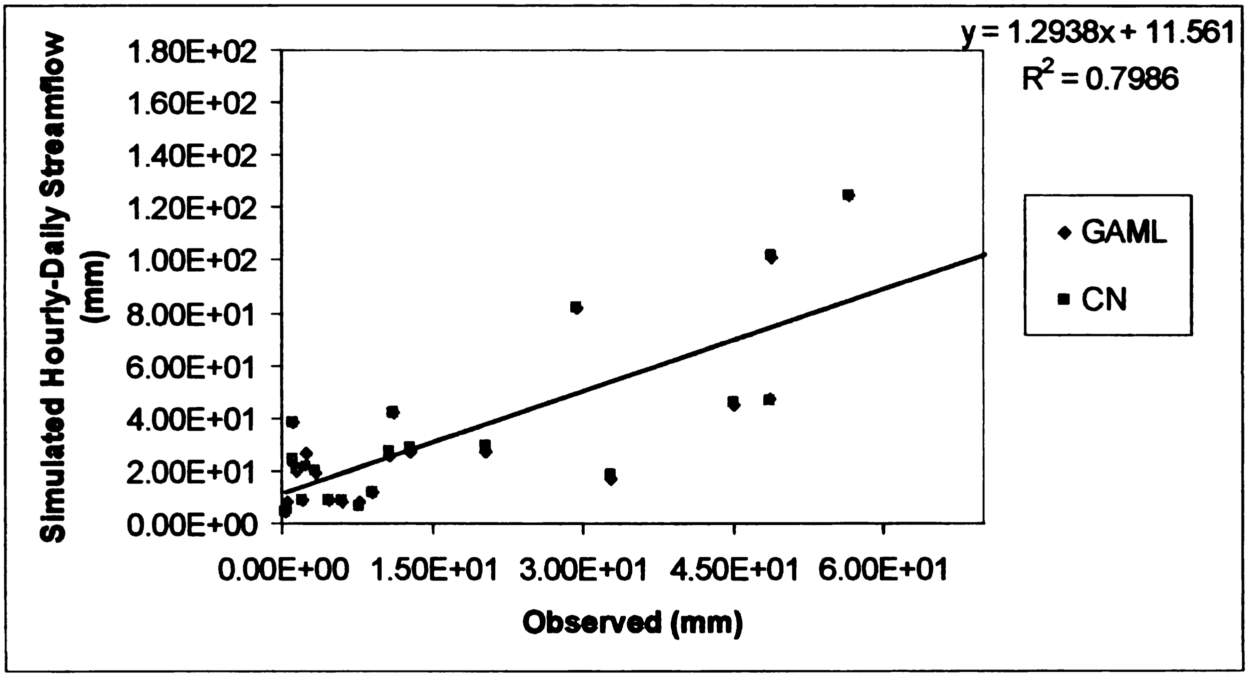

Figure 11:Simulated daily and hourly versus observed monthly streamflow at the outlet of VRW using calibrated GAML and CN for two-year period from 1980-1981

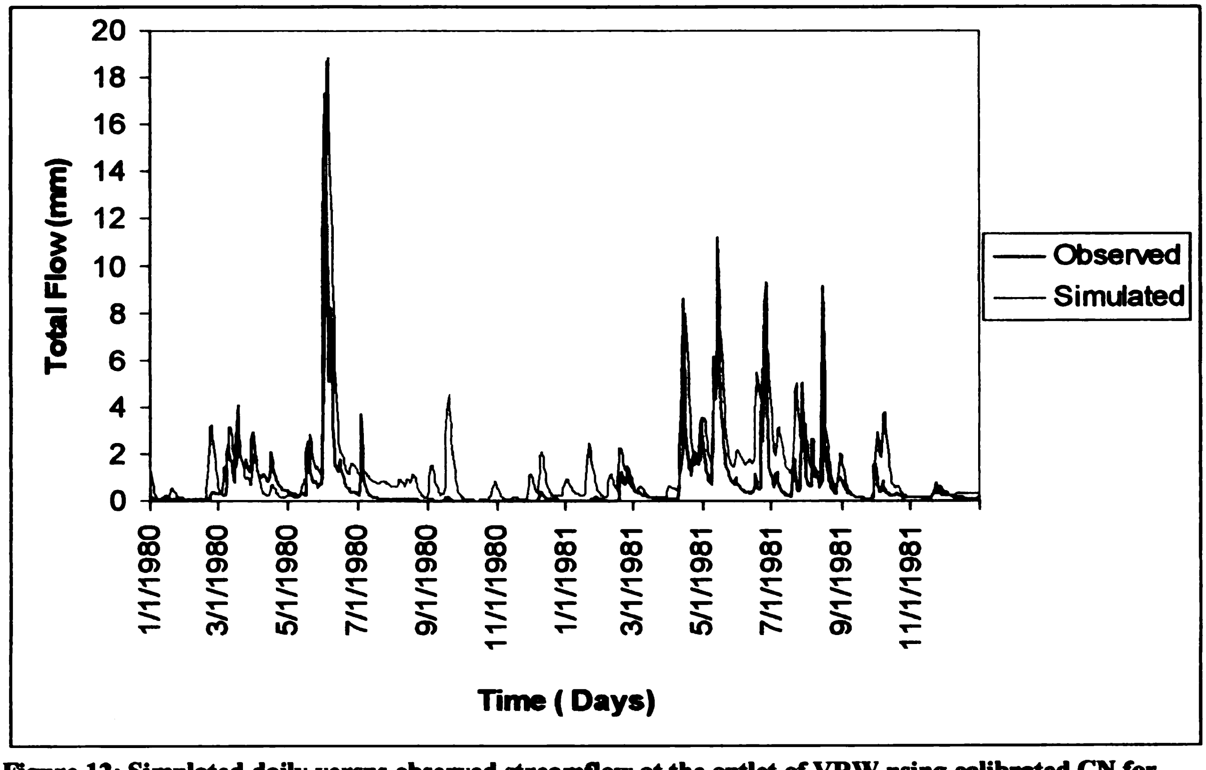

Figure 12: Simulated daily versus observed streamflow at the outlet of VRW using calibrated CN for a daily period from 1980-1981.

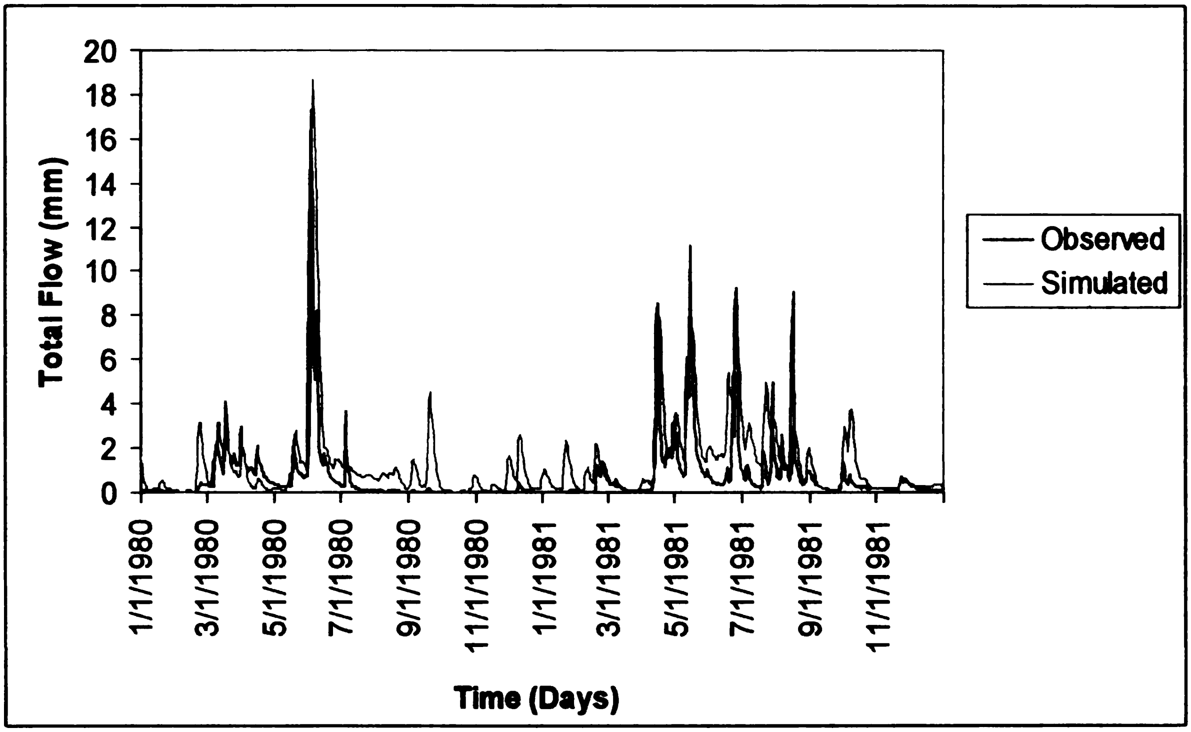

Figure 13: Simulated hourly versus observed streamflow at the outlet of VRW using calibrated GAML for a daily period from 1980-1981.

4.3 Validation

The validation procedure consisted of evaluating both GAML and CN modeling approaches using the calibrated curve numbers on a time series of data outside of the calibration time period. The years 1982 and 1983 were chosen. An R^2 of 0.2368 was determined for the daily streamflow at the outlet of the VRW using the Curve Number approach, and an R^2 of 0.2219 was determined for the hourly streamflow.

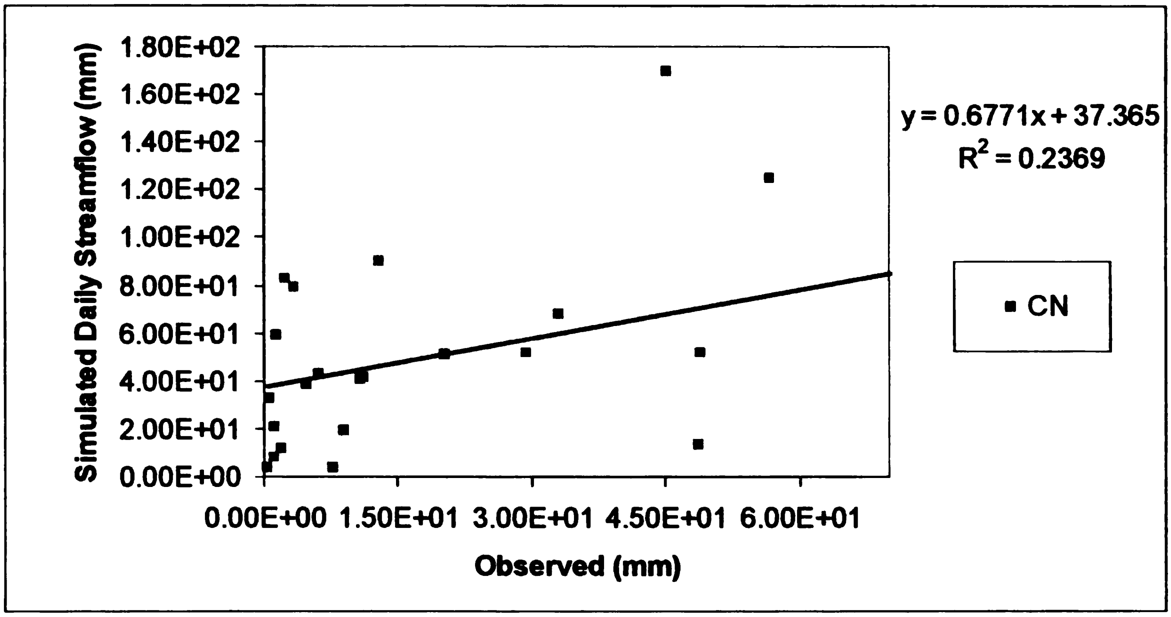

Figure 14:Simulated versus observed validated monthly stream flow time series at outlet of VRW using validated CN methodology for two year period from 1982-1983.

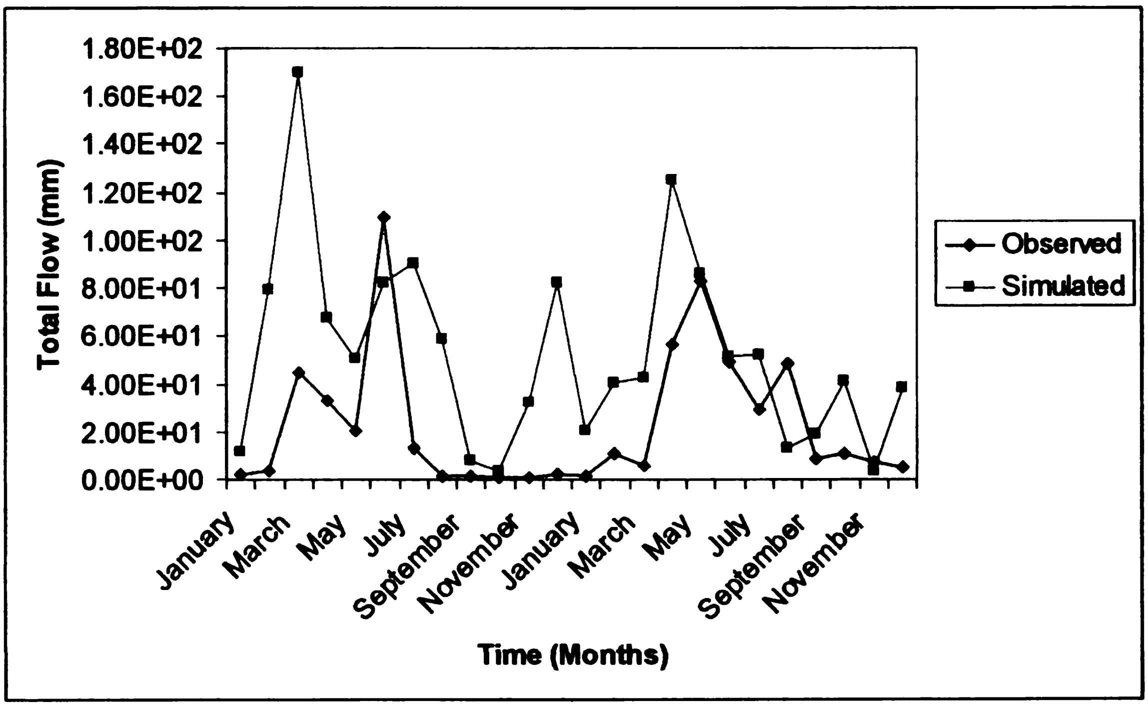

Figure 15: Observed and CN simulated monthly stream flow time series at outlet for validated VRW for time period 1982-1983

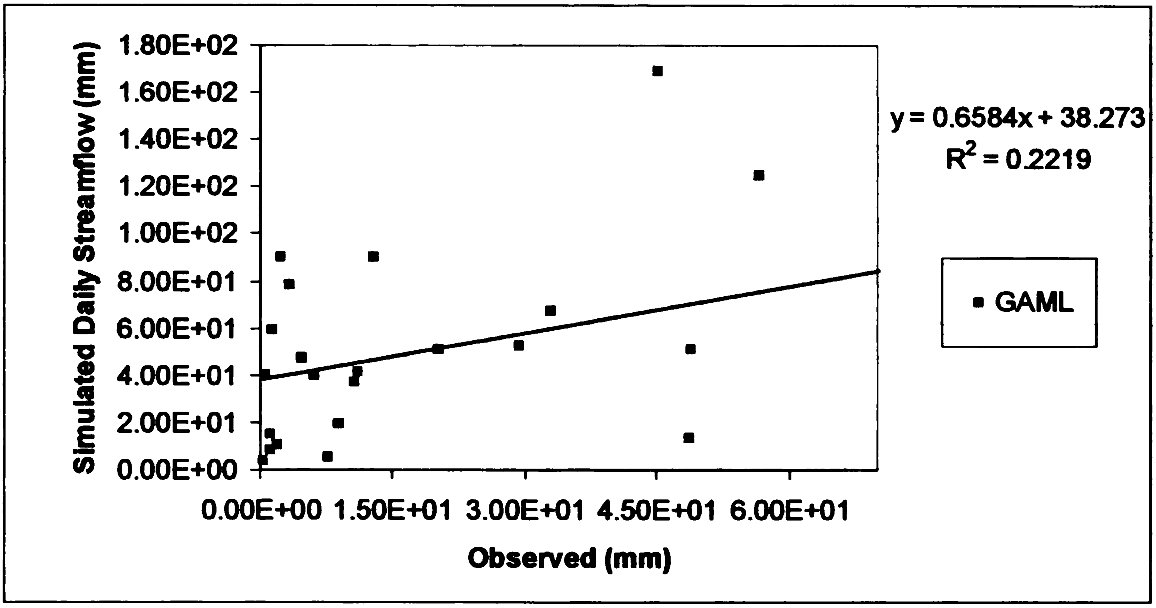

Figure 16: Simulated versus observed monthly surface streamflow time series at outlet of VRW using validated GAML methodology for two year period from 1982-1983

A positive slope of 0.65 is good indicator that the model is working; however the low R^2 is an indicator that it is not modeling to its full potential.

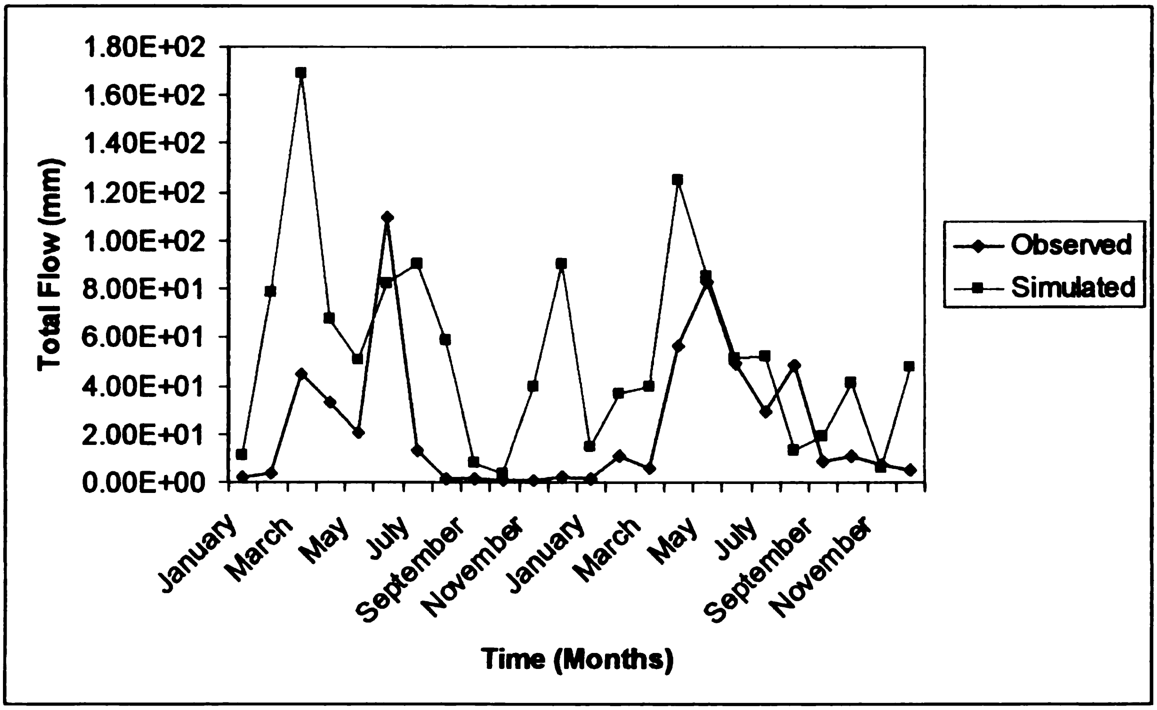

Figure 17: Observed and GAML simulated monthly surface streamflow time series at outlet for validated VRW for time period 1982-1983

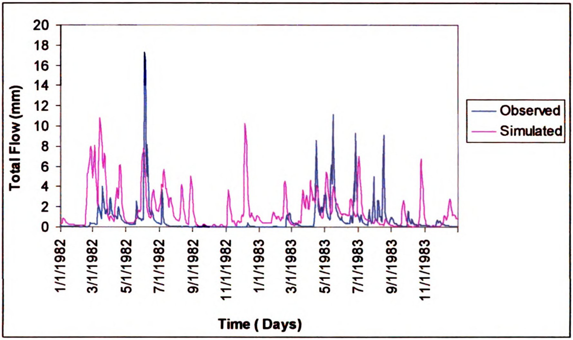

Figure 18: Simulated daily versus observed streamflow at the outlet of VRW using validated CN daily period from 1982-1983.

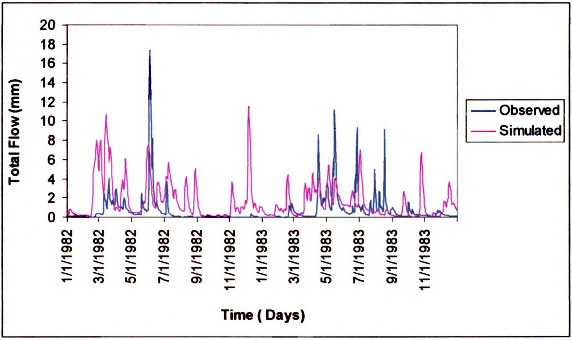

Figure 19: Simulated hourly versus observed streamflow at the outlet of VRW using validated GAML daily period from 1982-1983.

For this two year time period the R^2 and Nash-Sutcliffe efficiencies were 0.2219, and -1.23, respectively.

4.3 Streamflow Discussion

The results of this study demonstrated that the SWAT model could produce nearly identical results using both the Green-Ampt and Curve Number methods. The main difference is that similar amounts of flow were achieved but with different curve numbers with the Green-Ampt method calibrating to a higher curve number value. Overall, the model performed well (R^2 = 0.72 and NSE = 0.53) when comparing daily simulated data to observed data. The model performed especially well during wet periods. When there were large observed peak flows during wet periods the model generally simulated these well. Overall it appeared that the SWAT model underestimated the peak flows. Part of this discrepancy could be that the model predicts peak flows using a modified Rational Method, which is a somewhat simplistic approach which is generally acceptable for small urban watersheds, but in the case of a large, poorly drained watershed may not be as applicable. Another possibility could be that being such a large watershed with so few rain gages, there could have been more variability in rainfall amounts across the watershed that was not picked up by the three gages in the network.

There is also a noticeable trend in the data where the model simulates a substantial flow event where in reality there is little response in observed streamflow. There are several possibilities for this occurrence. One possibility is there was much more rainfall recorded at the gages than occurred over uninstrumented portions of the watershed. Another reason may be that the soil water content was overestimated. Especially during the summer, there is generally little watershed response to rainfall unless a large rainfall event occurs. The poorly drained soils have a tremendous water holding capacity. Perhaps this is not being reflected accurately by the soil characteristics in the model. There was a noticeable disagreement between the model and observed data during colder months, suggesting that the model was not simulating well during frozen soil conditions.

This research has shown that tile drained watersheds act differently than a traditional surface drained watershed. Originally the soils within this watershed had been classified as a "D" hydrologic group soil with high runoff potential. With the installation of subsurface drainage, conventional wisdom suggested that they should behave from a runoff standpoint as a "B" hydrologic group soil with less runoff potential. Hence, for the growing season the curve number should decrease from 91 for a D soil in poor hydrologic condition to a curve number of 78 for a B soil in good hydrologic condition and during the fallow season the curve number should decrease from 94 to 86. The results in this study have shown that when analyzing these types of watersheds, while the actual surface runoff decreases immensely due to the tile drains, the overall water balance of the watershed is still similar as the un-drained case, because water that would have runoff the land is infiltrating, and a large percentage of it is being captured by drain tiles and making its way back into the stream system.

5 CONCLUSIONS

5.1 General Conclusions

5.1.1 Advantages and Disadvantages of Green & Ampt and Curve Number Methods

The Green & Ampt method has been used successfully to predict stream flow in small watersheds (King et al., 1998), and the Curve Number approach used more frequently to determine stream flow in larger watersheds. The CN is a simple way of estimating stream flow, however it does not account for intensity and duration of the rainfall event. The GAML includes the intensity and duration and has been proven a good estimator when there is a flood routing and peak discharge (King et al., 1998). The GAML method is a physically based model, where the CN is empirical. However, timely adjustments need to be made to the rainfall data for the GAML which can be hard to interface with SWAT.

The GAML was used in conjunction with SWAT to account for the excess streamflow that occurs in tile drained fields during large storm events. It allows for the user to define the time step, which were set at 18 years and 30 minute intervals for this study. The model was calibrated for both the GAML and CN methods for the 579 mi^2 Vermillion River Watershed. Total monthly surface streamflow for the calibrated years 1980 and 1981 were compared to observed data at the outlet of the watershed for the two-year period.

Neither of the methods showed a significant deviation from the mean for the calibrated time period, and both were found to work equally well resulting in R^2 values of 0.81 for the Curve Number Method and 0.79 for the Green & Ampt Method when comparing total monthly flows to the observed data. Both methods tended to overestimate the peak flows for the duration of the year, and had low R^2 values for the colder weather periods. Simulation with the GAML did not perform well in the colder months, leading to R^2 values of 0.138, 0.00135, and 0.0029 for the months of January, February, and March in 1980. This suggests that the GAML method is limited seasonally, especially during periods of snow melt where the infiltration rate may not be calculated properly due to the models inability to account for frozen soils, R^2 values for the CN method were much higher for these months ranging from 0.57 in January, 0.643 in February, and 0.163 in March. This trend was also observed for both methods in 1981.

5.1.2 SWAT Model Uncertainty

Overestimation of the peak flows could be due to a number of factors; The soils in the watershed are predominantly clay, which means that there is little infiltration to the tiles and more surface streamflow. The model could be overestimating the peak flow because it cannot take into account the rate at which the water is moving over the surface of the landscape. This is seen in the high curve numbers that occurred when the model was calibrated, 89 for the Curve Number Method and 91 for the Green & Ampt, though these numbers reflect the values for cultivated land with C and D soils (Haan et al., 1994), they tend to be on the high side for agricultural land with conservation methods such as tile drains. The GAML method also needs extensive soils data so that it can define and determine the behavior of the stream flow in correspondence with the observed data (King et al., 1998).

Another factor that could have lead to discrepancies is the precipitation data. It is difficult for the SWAT model to accurately depict the pattern of rainfall over a watershed due to limited resolution of the precipitation data and poor spatial distribution of raingages (Borah et al., 2005).

Since the rainfall had to be calibrated for the two-year period there could be inaccuracies in the resulting data that was used. The three raingages had conflicting data for some of the days. This could mean that the rainfall was not collected, that there were differences in the rainfall for the three locations, or that too little rainfall was collected and it was documented as zero. This could be a possible source of the lag time in the model. The model tends to be about one day behind the observed data, which could be attributed to the discrepancies in the way that the rainfall was collected.

Tile drainage component may also be a contributing factor in the error since they may not reflect the actual landscape and how the tiles are spaced and placed. The actual locations of the tiles are unknown, and the model was calibrated for tile drainage along with the observed data.

3.3 Future Considerations

This study also identified an error with SWAT that has not yet been addressed in related studies, since further calibration of the model parameters is necessary to obtain better model results. It was discovered when calibrating the model that changing the growing season CN had no effect on the flow at the outlet. The only parameter that had an effect was the Fallow season operation. Since plant growth significantly affects the flow from the surface, it was important to resolve this issue. The issue was resolved by the SWAT programmer who resides in Texas, and had never before been brought to his attention. There is a possibility that other errors have stemmed from this, or are not addressed.

There is also an issue with the channel routing using the hourly rainfall data. They GAML method does not consider this when calculating the flow. Channel routing accounts for the travel time of the rainfall by routing hydrographs through channels such as ditches or tile drainage. SWAT uses the Muskingum method which assumes a single stage-discharge relationship. This may not be valid for all flow situations, and caused the GAML method to run inaccurately when it was turned on in SWAT.

This research focused only on the rainfall component of tile drainage, considerations might be made to look into the responsiveness of nitrate in tile drained watersheds. Nitrate has the possibility of leaching differently than rainfall, and understanding the reactions a tile-drained watershed might have to the application of large amounts of nitrate may be beneficial in future work. It would aid in the understanding of travel time, and concentrations in streamflow which have led to hypoxic conditions in the Gulf of Mexico.

APPENDICES

Appendix A: SWAT Output.std Parameters

APPENDIX A

SWAT Output.std Parameters

Precip: Total amount of precipitation falling on the HRU during time step (mm H_2O).

Sur Q: Surface streamflow generated in HRU during time step (mm H_2O).

Lat Q: Lateral flow contribution to stream flow (mm H_2O). Water flowing laterally within the soil profile that enters the main channel during time step.

GWQ: Groundwater contribution to stream flow (mm H_2O). Water from the shallow aquifer that enters the main channel during the time step. Groundwater flow is also referred to as baseflow

Late

SW: Soil water content (mm). Amount of water in the soil profile at the end of the time period.

ET: Actual evapotranspiration (soil evaporation and plant transpiration) from the HRU during the time step (mm H_2O).

PET: Potential evapotranspiration (mm H_2O). Potential evapotranspiration from the HRU during the time step.

Water Yield: Water yield (mm H_2O). Total amount of water leaving the HRU and entering main channel during the time step. (WYLD = SURQ + LATQ + GWQ – TLOSS – pond abstractions)

SED Yield: Sediment transported with water into reach during time step (metric tons), and Sediment transported with water out of reach during time step (metric tons).

NO3 Sur Q: NO_3 in surface streamflow (kg N/ha). Nitrate transported with surface streamflow into the reach during the time step.

NO3 Lat Q: NO_3 in lateral flow (kg N/ha). Nitrate transported by lateral flow into the reach during the time step.

NO3 Perc: NO_3 percolated flow (kg N/ha). Nitrate transported by percolation into the reach during the time step.

NO3 Crop – NO_3 utilized by the crop (kg N/ha). Nitrate utilized by the crop during the time step

N Organic: Organic N yield (kg N/ha). Organic nitrogen transported out of the HRU and into the reach during the time step.

Soluble P: Soluble P yield (kg P/ha). Soluble mineral forms of phosphorus transported by surface streamflow into the reach during the time step.

Organic P: Organic P yield (kg P/ha). Organic phosphorus transported with sediment into the reach during the time step

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