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Research Paper Title	Modeling the Potential Influence of Subsurface Tile Drainage Systems on Downstream Flooding in a Midwestern Agricultural Watershed		
M.S. or Ph.D.	M.S.	**Expected Date of Graduation (month/year)**	August 2023

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I attest that the student named above is a member of ASABE, was enrolled in a graduate program in our department for at least four months between March 15 of this year and March 15 of the previous year and the paper being submitted is based on research completed for either M.S. or Ph.D. degree.

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MODELING THE POTENTIAL INFLUENCE OF SUBSURFACE TILE DRAINAGE SYSTEMS ON DOWNSTREAM FLOODING IN A MIDWESTERN AGRICULTURAL WATERSHED

Highlights

- Tile flow was simulated in a midwestern, agricultural watershed to study the impacts of subsurface tile drainage on watershed hydrology and downstream flooding.
- Five scenarios with varied extents of tile-drained agricultural land were simulated and compared with a baseline scenario.
- Increasing tile-drained area resulted in modified watershed hydrology, including increased tile flow contribution to total streamflow.
- The impact of tile drainage on downstream flooding suggests that subsurface drainage systems decrease daily flood events (or flood days) across the studied scenarios.

Abstract. *Subsurface tile drainage systems are common in agricultural regions of the Midwestern United States. Drainage systems remove excess water from the surface and soil profile of agricultural fields, allowing crop production in previously unsuitable locations. Drainage systems, however, impact watershed hydrology and could, depending on site-specific factors, influence flooding events. Therefore, this study determines whether subsurface tile drainage systems influence downstream flooding from a midwestern, agricultural watershed: Skunk Creek watershed. The Soil and Water Assessment Tool (SWAT) model is used to simulate the hydrologic processes of Skunk Creek Watershed—using topography, land use, soil, and weather input data—for a period of 18 years (2004-2021). The model is calibrated and validated using observed daily streamflow data with the SWAT Calibration and Uncertainty Program (SWAT-CUP) software. The statistical parameters Nash Sutcliffe Efficiency (NSE), Percent Bias (PBIAS), and RMSE-Observations Standard Deviation Ratio (RSR) are used to evaluate the fit and accuracy of the model. The calibrated and validated model performs satisfactorily, except for several high-flow events. Five tile drainage scenarios—ranging from 15% to 75% tile-drained agricultural land—are individually incorporated into the model. As the drained area increases, the volume of tile flow contributing to daily streamflow increases. Additionally, surface runoff, groundwater flow, deep aquifer recharge, and percolation decrease, while lateral soil flow and evapotranspiration increase. A comparison of tile drainage scenarios suggests that increasing the amount of tile-drained land decreases total flood events (flood days). While tile flow decreased flood days on a daily time-step, flash floods might have occurred on a sub-daily time-step, but were not captured in this study. Future studies can replicate the approach with a sub-daily time-step for simulating hourly flood events with various tile drainage scenarios.*

Keywords. *Streamflow, SWAT, Tile drainage, Upper Midwest, Watershed hydrology*

INTRODUCTION

Subsurface drainage is a common water management practice widely used in the Midwestern United States with the primary purpose of increasing crop yields (Dinnes *et al.*, 2002; Blann *et al.*, 2009; Ghane *et al.*, 2012). More than 30% of agricultural land in the Midwest (Vidon and Cuadra, 2010; King *et al.*, 2014; Sloan *et al.*, 2016) are managed with subsurface drainage (Jaynes and James, 2007; Naz *et al.*, 2009; Sloan *et al.*, 2016). By removing excess water from the root zone (Zucker and Brown, 1998;

Fraser *et al.*, 2001; King *et al.*, 2014), subsurface drainage systems alter watershed hydrology with both positive and negative impacts on downstream water quantity (Macrae *et al.*, 2007; King *et al.*, 2014) and quality (Baker *et al.*, 2004; Ahiablame *et al.*, 2011).

The impacts of subsurface drainage on the natural hydrologic regime are characterized by changes in the water balance, including increased infiltration, increased soil water storage, decreased surface runoff, and increased evapotranspiration (ET) (Vidon and Cuadra, 2011; Sloan *et al.*, 2016; Yang *et al.*, 2017), and may lead to homogeneity in such responses across different soil types (Sloan *et al.*, 2016). For example, under relatively small storm events with dry antecedent moisture conditions, increased infiltration and decreased surface runoff will likely prevail on drained soils compared to undrained soils (Sloan *et al.*, 2016). In contrast, subsurface drainage may not considerably affect infiltration under large and intense rainfall events (Blann *et al.*, 2009; Sloan, 2013). Land conversion and drainage for intensive agricultural use has been shown to decrease in-field runoff, but increase peak runoff rates in streams (Skaggs *et al.*, 1994; Wiskow and van der Ploeg, 2003; Blann *et al.*, 2009). The decreased runoff within the field has been attributed to the increased capacity of drained soils to temporarily store moisture, allowing more water to infiltrate into the soil profile (Zucker and Brown, 1998; Fraser *et al.*, 2001), which in turn reduces local flooding (i.e. in the field) but may contribute to increased annual downstream flows (King *et al.*, 2014).

Between 2005 and 2010, King *et al.* (2014) found that subsurface drainage accounted for 47% of the total monthly discharge in the Upper Big Walnut Creek watershed near Columbus, Ohio. In Strawberry Creek watershed in Ontario, Macrae et al., (2007) found subsurface drainage contributed between 0 to 90% of seasonal discharge and 40% annual discharge of the watershed. Approximately 20 to 87% of peak flow reductions were linked to subsurface drainage in the Midwest depending on the soil type and antecedent moisture conditions (Skaggs and Broadhead, 1982; Fraser *et al.*, 2001; Vidon and Cuadra, 2010). In a field-scale study in the United Kingdom, Robinson and Rycroft (1999) observed reductions in peak flow rates in clayey soils and increased peak flow rates in sandy soils. Using advanced ET mapping techniques based on remote sensing, Yang *et al.* (2017) determined that subsurface drainage appears to decrease ET during the early growing season but substantially increase crop water use during the mature crop growth stage. The authors linked the differences in ET water losses to more water content in the soil from winter snowmelt and early spring rainfall events available to the crop in early stage compared to elevated crop water demand during the peak growing season.

Concerns have long been raised regarding the role of subsurface drainage in downstream flow alterations and subsequent flooding events at the watershed scale. Two schools of thought have often been debated regarding the hydrologic and environmental impacts of subsurface drainage (Blann et al., 2009). With changes in the amount and timing of water leaving the field, surface runoff may decrease (Zucker and Brown, 1998; Macrae *et al.*, 2007; Maalim and Melesse, 2013), while peak flow rates may increase (Konyha *et al.*, 1992; Blann *et al.*, 2009; Wesström *et al.*, 2014), leading to downstream flooding through acceleration of water delivery to the receiving rivers (Whiteley, 1979; Blann et al., 2009). On the contrary, subsurface drainage as a water management practice removes extra moisture from the soil profile, allowing more infiltration and less downstream flood flow (Irwin and Whiteley, 1983; Fraser *et al.*, 2001; King *et al.*, 2014). In light of the two conflicting points of view, a logical question is to explore the extent to which streamflow changes can be explained by subsurface drainage, under the null hypothesis that subsurface drainage does not affect downstream flood flow. Therefore, the objectives of this study were to (1) model subsurface drainage systems on varied extents of agricultural land in a midwestern, agricultural watershed and (2) analyze the effects of increased tile-drainage on watershed hydrology and daily downstream flooding events.

Materials and Methods

Study Area

This study was conducted in Skunk Creek watershed (Figure 1), located in southeastern South Dakota, USA. The watershed is located within 96.74º and 97.35°W latitude and 43.45° and 44.13° N longitude, and drains an area of approximately 1606 km^2. The average annual precipitation in Skunk

Creek watershed during the 2007-2021 study period was 729.14 mm (PRISM Climate Group). Relatively, the average annual streamflow at the outlet of the watershed was 5.80 m^3/s with a maximum annual streamflow of 195 m^3/s. The average daily temperature in Skunk Creek watershed ranged from -34.4℃ during the winter to 40.7℃ during the summer, respectively. Skunk Creek, a tributary of Big Sioux River, supports agriculture in this watershed as well as surrounding areas. The watershed is intensely used for crop production (65% of land) with predominantly agricultural row crops of corn and soybeans (NLCD 2019). The soils of the watershed are dominated by gently sloping Egan and Moody silty clay loams belonging to hydrologic soil group "B" (SSURGO).

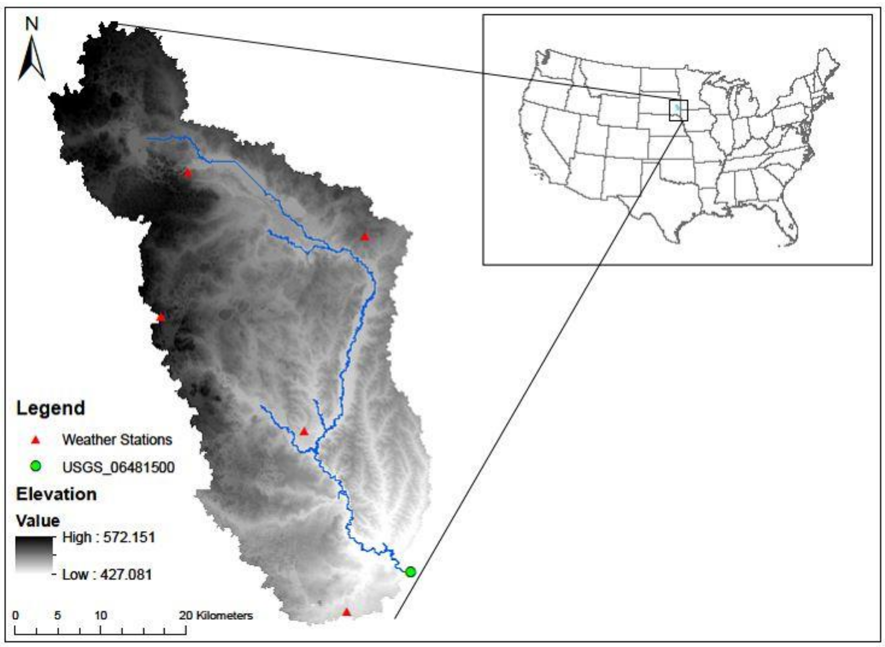

Figure 1: Map showing location of Skunk Creek watershed in South Dakota, USA; USGS streamflow gauge station at the watershed outlet; and respective weather stations

SWAT MODEL

ArcGIS version 10.7.1 with SWAT 2012 (SWAT 2015) version revision 681 was used in this study. SWAT is a watershed-scale, physically-based, semi distributed hydrologic model developed to simulate the impacts of land use and management practices on water quantity and water quality over a continuous time scale (Gassman et al. 2007). The model has been widely used in hydrologic and water quality studies around the world (Jha et al. 2007; Abbaspour et al. 2007; White and Chaubey, 2005), and has proven to be proficient in studying the long-term impacts of land use change, subsurface drainage, and climate change scenarios (Neitsch et al. 2011; Arnold et al. 2012). The SWAT model can be executed at daily, monthly, and sub-daily time steps, depending on the availability of input data at the respective time scale.

ArcSWAT (Olivera et al. 2006; SWAT 2015) is a GIS-based graphical input interface which is used to delineate and execute the SWAT model in an ArcGIS environment. In SWAT, a watershed is divided into sub-watersheds and then further subdivided into Hydrologic Response Units (HRUs). In a sub-watershed, areas of the same land use, soil type, and slope (Neitsch et al., 2011) are combined into one HRU, and various hydrologic, sediment, and nutrient processes are able to be simulated. The SWAT model is able to simulate subsurface drainage using tile drainage equations that have been integrated, verified, and evaluated (Moriasi et al., 2007a; Moriasi et al., 2012). In this study, the physically-based Hooghoudt (1940) and Kirkham (1957) tile drainage equations were used. The simulation of tile flow from these equations is based on three conditions, (1) if the water table is below the soil surface and the depth of ponded water in surface depressions are less than maximum depressional storage, the Hooghoudt equation simulates drainage, (2) if the ponded depth in surface depressions is greater than maximum depressional storage, and the water table rises over the soil surface and stays for a long time, the Kirkham equation simulates drainage, and (3) if the estimated drainage by the previous two equations is greater than the drainage coefficient, the flow will be equal to the drainage coefficient (Boles, 2013; Guo et al., 2018; Rahman, 2011; Rahman et al., 2011).

SWAT Input Data and Model Set-Up

In order to study the impacts of subsurface tile drainage systems on downstream flooding in Skunk Creek watershed, a SWAT model was set up for an 18-year period (2007-2021). The data requirements of a SWAT model include topography, soils, land use, weather, and observed streamflow.

Topography, Soil, and Land Use Land Cover Data

In this study, a 10-meter digital elevation model (DEM) for South Dakota was downloaded from the USDA Natural Resources Conservation Service (NRCS). The 2019 National Land Cover Dataset

(NLCD) was downloaded from the Multi-Resolution Land Characteristics Consortium, and Soil Survey Geographic Database (SSURGO) data was downloaded from the USDA-NRCS Web Soil Survey for all six counties within Skunk Creek watershed.

Weather Data

Weather data requirements of the SWAT model include minimum temperature, maximum temperature, and daily precipitation for the study period. This data was obtained from the PRISM Climate Group Northwest Alliance for Computational Science and Engineering—managed by Oregon State University—for the years 2004-2021 (PRISM Climate Group).

PRISM climatic data was downloaded for five counties—Lake, Lincoln, McCook, Minnehaha, and Moody—in Skunk Creek watershed. Gridded data was downloaded for only the area of each county within the watershed. The values for minimum temperature, maximum temperature, and precipitation were averaged, and then indicated at the centroid of each county as a weather station. All other climatic components required by SWAT—solar radiation, windspeed, and relative humidity—were simulated using the built-in SWAT model weather generator.

Observed Streamflow Data

Observed daily streamflow data was downloaded from streamflow gauge station USGS 06481500 located at the outlet of the watershed (USGS). Daily streamflow data from 2004-2021 was used to calibrate and validate the SWAT model.

MODEL SET-UP, CALIBRATION, VALIDATION, AND EVALUATION

The watershed was delineated into eight sub-basins and 1288 HRUs. The SWAT model was calibrated (2007-2018) and validated (2019-2021) at a daily time-step for streamflow at the watershed outlet using observed data. The first three years (2004-2006) were used as the warm-up period to minimize uncertainty and stabilize the model before simulation (Mehan et al., 2017). The SUFI-2 auto-calibration method, which is part of the stand-alone SWAT Calibration and Uncertainty Program software (SWAT-CUP; Abbaspour, 2015), was used to calibrate and validate the model. SWAT-CUP is used for sensitivity analysis, uncertainty analysis, and calibration and validation of SWAT model parameters. The SUFI-2 method has been widely and successfully used for SWAT calibration in recent SWAT studies in Skunk Creek watershed and surrounding watersheds (Mehan et al., 2016; Teshager et al., 2016) due to its ability to calibrate the model in less time compared to other SWAT-CUP methods (Yang et al., 2008).

In the SUFI-2 algorithm, the objective function was set to maximize the Nash Sutcliffe Efficiency (NSE; Nash and Sutcliffe, 1970) between simulated and observed values of daily streamflow. The values of the calibrated parameters with the "best fit"—as determined by SWAT-CUP—were entered directly into the developed SWAT model. The parameters used for calibration and validation, along with their initial minimum and maximum range (Table 1), were selected based on previous studies conducted in and around the study area, as well as on other Midwestern agricultural watersheds (Mehan et. al., 2016; Rajib et. al., 2016; Hutchinson and Christiansen, 2013; Neupane and Kumar, 2015).

The performance of the model was evaluated by calculating the NSE, Percent Bias (PBIAS; Gupta et al., 1999), and Root Mean Square Error-Observations Standard Deviation Ratio (RSR)**,** along with qualitative evaluation (Moriasi et. al., 2007; 2015) based on plotting the time series of daily simulated and observed streamflow. In addition, streamflow calibrations were constrained using soft data (Arnold et al., 2015) such that the SWAT-CUP parameters and simulated ET values were realistic and representative of the study area in order to minimize the potential for false positive outcomes (obtaining good statistics for the wrong reasons) (Kischner, 2006; Moriasi et al., 2015). In this study, the model was constrained such that simulated values were within 15% of the average annual ET soft data value of 630 mm (Paul et al., 2016).

Table 1: Parameters used in SWAT model calibration and validation for daily streamflow

Parameter*	Definition	Minimum Value	Maximum Value	Fitted Value
R_CN2	Curve number (moisture condition II)	-0.20	0.20	0.095
V_ALPHA_BF	Baseflow alpha factor	0.00	1.00	0.487
V_GW_DELAY	Groundwater delay time (days)	30.0	450	42.08
V_GWQMN	Depth of water in shallow aquifer	0.00	2.00	0.725
V_GW_REVAP	Groundwater "revap" coefficient	0.02	0.20	0.172
V_REVAPMN	Threshold depth of water in shallow aquifer	0.00	500	40.33
V_CH_N2	Manning's "n" value for main channel	0.01	0.30	0.312
V_CH_K2	Effective hydraulic conductivity in main channel (mm/hr)	-0.01	500	267.3
V_OV_N	Manning's "n" value for overland flow	0.01	1.00	0.342

V_ESCO	Soil evaporation compensation factor	0.00	1.00	0.480
V_EPCO	Plant uptake compensation factor	0.00	1.00	0.603
A_SOL_AWC	Available water capacity of soil layer	0.00	1.00	0.405
V_SURLAG	Surface runoff lag coefficient	0.05	24.0	6.950
V_SMTMP	Snow melt base temperature	-5.00	5.00	-4.385
V_SFTMP	Snowfall temperature	-5.00	5.00	0.185
V_SMFMX	Melt factor for snow on June 21 (mm H_2O/°C-day)	1.40	7.50	3.265
V_SMFMN	Melt factor for snow on December 31 (mm H_2O/°C-day)	1.40	7.50	1.666
V_TIMP	Snow pack temperature lag factor	0.00	1.00	0.068

* - The qualifier 'V' indicates that the original value was replaced by a value from the range; 'A' indicates that the original value was added to a value within the range; and 'R' indicates that the original value was multiplied by 1+ a value from the range.

FLOOD RISK MODELLING

Flood risk is usually quantified by the number of flood events and the duration of such events. Following Schilling *et al.* (2014), a flood event is defined as a simulated stream discharge at the watershed outlet which exceeds a specified flood stage. The event may last a few minutes to hours and days, and represents any flood type (i.e. action, moderate, and major). Flood duration is the number of minutes, hours, and days a given flood event lasts on occurrence (i.e. the total number of minutes, hours, and days a given flood event stays above the defined flood stage in a year over the study period). In this study, only daily flood events, or flood days, were considered. Flood days are streamflow events that reach a specified flood stage and maintain the stage for an entire 24-hour period.

The USGS has established flood stages for Skunk Creek watershed. The "Action Flood Stage" is defined as 2.90 m, the "Flood Stage" is defined as 3.51 m, the "Moderate Flood Stage" is defined as 4.57 m, and the "Major Flood Stage" is defined as 5.18 m (NOAA, n.d.). To assess the impact of subsurface drainage on downstream flooding, a relationship was developed between observed daily streamflow and river stage. The stage-discharge relationship was used to determine the stream discharge that corresponds to the defined flood stages. The stage heights of 2.90 m, 3.51 m, 4.57 m, and 5.18 m were found to correspond with streamflow values of approximately 78.0 m^3/s, 144 m^3/s, 184 m^3/s, and 190 m^3/s, respectively (Figure 2). Values for simulated streamflow in the baseline and tile drainage scenarios that exceed the flood discharge threshold were considered as flood events. The frequency of such events was determined by counting the number of times river discharge peaked above any defined flood stage over the study period and maintained it for one complete day.

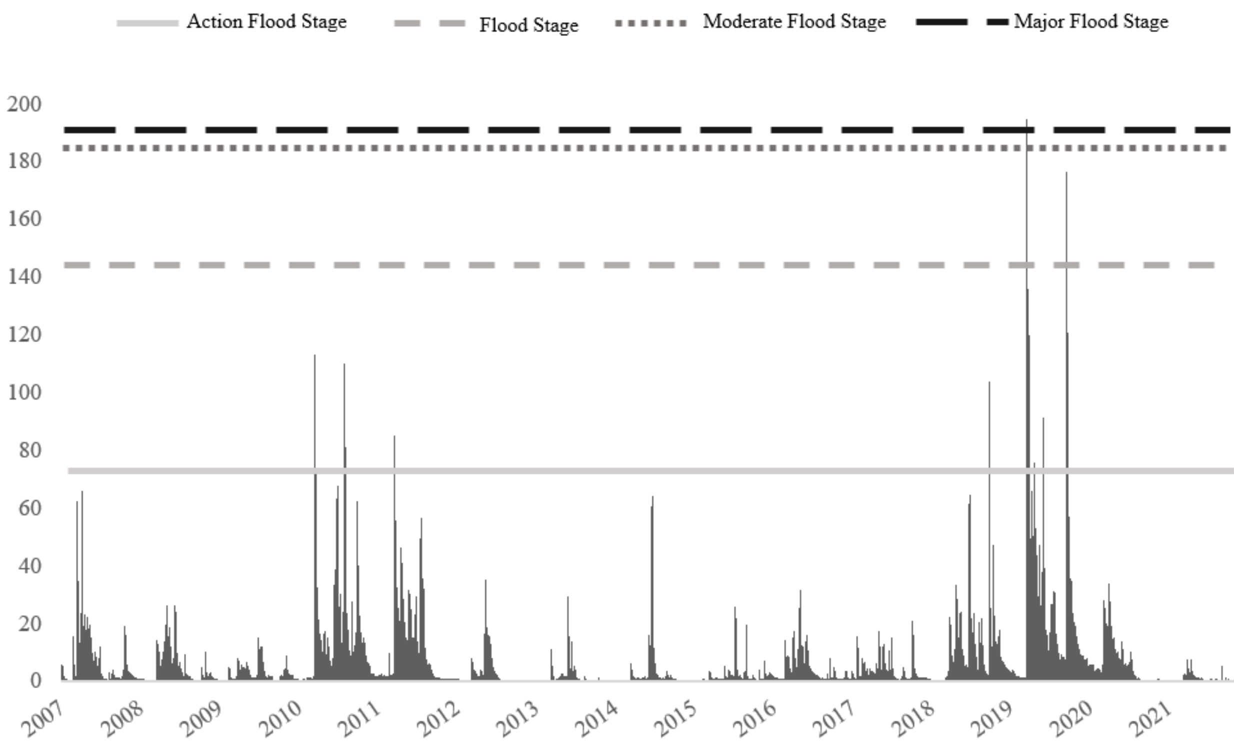

Figure 2: Observed hydrograph for daily streamflow (2007-2021) for Skunk Creek watershed showing "Action Flood Stage" at 78 m^3/s, "Flood Stage" at 144 m^3/s, "Moderate Flood Stage" at 184 m^3/s, and "Major Flood Stage" at 190 m^3/s.

FLOOD ASSESSMENT SCENARIOS

A total of five scenarios were simulated to evaluate the impacts of subsurface drainage on downstream flooding. The baseline model has no subsurface drainage, and was constructed with calibrated and validated parameters based on 2019 land use data and 2007-2021 climate data. The five scenarios all have the same drainage depth (DDRAIN), drainage spacing (SDRAIN), and impermeable depth (DEP_IMP)—914.4 mm, 30,000 mm, and 1,000 mm, respectively—yet vary in their extent of agricultural land cover. The values of drainage depth and spacing were determined from literature (Kringen et al., 2021; University of Minnesota Extension, 2018) and the impermeable depth was set at a value slightly larger than DDRAIN (ArcSWAT Google Groups, 2014; Boles, 2013; Hutchinson & Christiansen, 2013). Additionally, the curve number (CN2) was reduced in all tile-drained HRUs by 30% to reflect infiltrated water contributing to tile flow (Frankenberger). The tile drainage scenarios increase at increments of 15%, and consist of 15% to 75% drained agricultural land in the watershed

(Table 2). During scenario development, subsurface tile drainage systems were implemented in all agricultural HRUs, despite the crop type. Drainage systems were first implemented in sub-watersheds located near the center of the watershed, then moved outward with each increasing scenario.

Table 2: Drainage design scenarios simulated in this study

Scenario Description	Scenario Notation
15% Tile-Drained Agricultural HRUs	Scenario 1
30% Tile-Drained Agricultural HRUs	Scenario 2
45% Tile-Drained Agricultural HRUs	Scenario 3
60% Tile-Drained Agricultural HRUs	Scenario 4
75% Tile Drained-Agricultural HRUs	Scenario 5

To ensure simulated tile flow was an accurate representation of the study area, it was compared with observed tile flow data from a similar midwestern, agricultural watershed, Bad River watershed. It is important to note that values for observed tile flow in Bad River watershed correspond to 100% tile-drained agricultural land. The observed tile flow data ranges from May 20, 2015 to October 15, 2015 and from April 14, 2016 to November 2, 2016. The average tile flow (mm/day) was calculated for each dataset as well as the minimum, maximum, and average values for the observed period. These values were then used to validate simulated tile flow for the corresponding time period.

RESULTS AND DISCUSSION

CALIBRATION AND VALIDATION

Simulated daily streamflow was compared with observed daily streamflow from the watershed outlet to ensure the calibrated model demonstrated the watersheds' hydrologic characteristics (Figure 3). In general, the simulated streamflow matched well with the observed data, except for several high-flow events (Figure 3). These findings are similar to previous studies conducted across different parts of the world where the researchers have found inconsistencies in SWAT performance under extreme flow conditions (e.g., Wang et al., 2008; Oeurng et al., 2011; Qiu and Wang, 2013; Rajib et al., 2016; Rajib et al., 2016a).

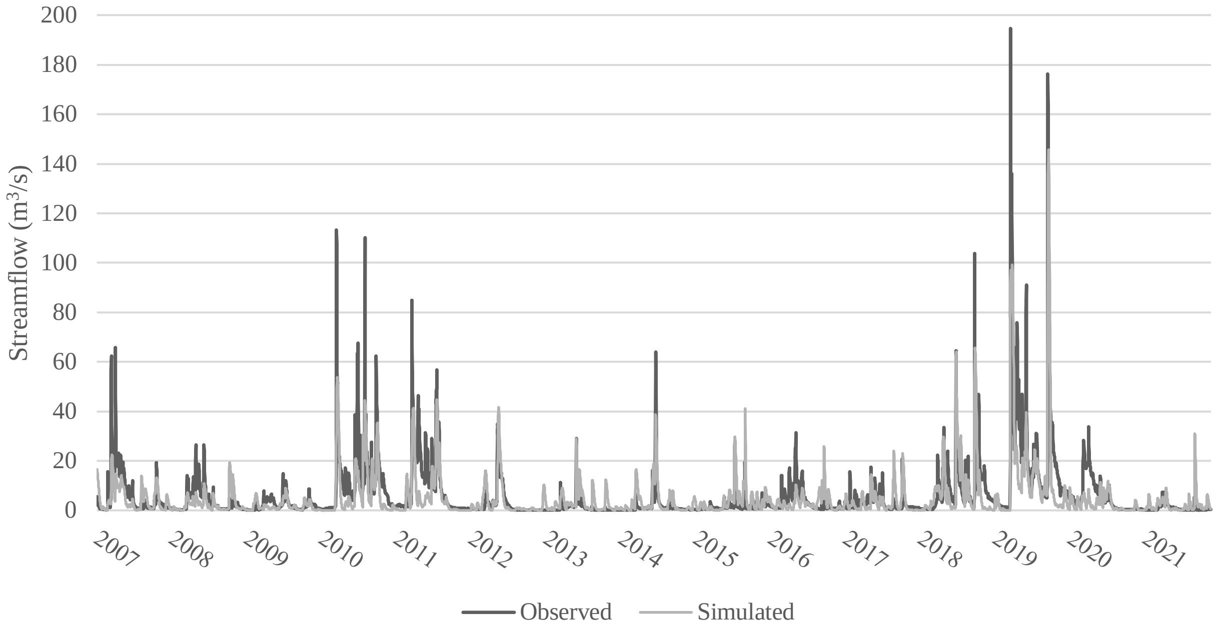

Figure 3: Comparison of observed and simulated daily streamflow for Skunk Creek watershed during calibration (2007-2018) and validation (2019-2021).

During the calibration and validation period, the NSE ranged from 0.510 to 0.750, the PBIAS ranged from 8.70 to 27.0, and the RSR ranged from 0.700 to 0.500. Validation statistics generally demonstrated model performance improvement from calibration statistics, and most of the values, except PBIAS, were satisfactory (Table 3; Moriasi et al., 2007). Although the SWAT model performed reasonably well according to NSE and RSR, a high positive daily PBIAS during the validation period is concerning. This high positive PBIAS indicates that the total volume of flow was overestimated at the outlet (Krause et al., 2005). This could be attributed to the issue of frequent snowmelt flash flows during spring in the study area and prevalence of low-flow condition during the rest of the year. Given the inherent complexity of simulating daily flows and the frequency of spring snowmelt, it can be said that the model performed satisfactorily during the calibration and validation time periods.

Table 3: Comparison statistics of daily, monthly, and annual simulated streamflow in Skunk Creek watershed to observed streamflow during the calibration and validation periods.

	Calibration (2007-2018)			Validation (2019-2021)		
	NSE	PBIAS	RSR	NSE	PBIAS	RSR
Daily	0.510	8.700	0.700	0.750	27.00	0.500
Monthly	0.583	8.831	0.089	0.761	26.67	0.275
Annual	0.665	-33.16	0.095	0.813	26.25	0.394

BASELINE AND TILE DRAINAGE SCENARIOS

When observing the watersheds' average annual water budget for the baseline scenario during the entire study period, evapotranspiration (ET) had the highest share, followed by surface runoff, groundwater flow, percolation, lateral soil flow, and deep aquifer recharge. As tile drainage was introduced in the watershed, surface runoff, groundwater flow, deep aquifer recharge, and percolation all decreased, whereas lateral soil flow, tile flow, and ET all increased. These results are similar to those observed by Paul et al., (2016); as tile drainage was introduced in the study watershed, the percolation decreased, while lateral flow and ET slightly increased.

The average annual simulated tile flow in Skunk Creek watershed ranged from 3.710 mm in Scenario 1 to 10.73 mm in Scenario 5. The results indicate that throughout tile drainage scenario analysis, the contribution of tile flow ranges from 4.13% of the average annual water yield to 15.43% of the average annual water yield. In 2015, observed values for minimum, maximum, and average tile flow in Bad River watershed were 0 mm, 0.007 mm, and 0.001 mm, respectively. The simulated values for the same 2015 period were all 0 mm. In 2016, observed values for minimum, maximum, and average tile flow were 0 mm, 0.109 mm, and 0.008 mm, respectively. The simulated values for the corresponding time period were 0 mm, 0.19 mm, and 0.02 mm, respectively. From these values, it can be determined that the simulated tile flow in Skunk Creek watershed is an accurate representation of tile flow in this region of the Midwest. However, the results of this study differ from most of the studies conducted in the heavily tile-drained watersheds of the Midwestern United States (King et al., 2015; Arenas-Amado et al., 2017; Thomas et al., 2016) which can be attributed to the fact that the topography and weather of the study area is quite different than the other studies referenced. Additionally, the short-lived peak flows from spring snowmelt are difficult to capture in tile flow.

Further investigation of the contribution of tile flow to streamflow showed a pronounced seasonality and varied from month to month (Figure 4). While the total contribution of tile flow to total flow was rather low, it is interesting to note that high tile flows occurred from March to October, whereas there was almost no tile flow from November to February, or the colder, late fall and winter months. These results are similar to those obtained by Schilling et al. (2019) for a study conducted in Iowa. The late spring and early summer months are dominant periods of tile drainage discharge in the Midwestern United States due to a combination of factors such as high spring precipitation, snowmelt, and decreased ET (Ikenberry et al., 2014). The spike in tile flows from August-October could be attributed to the senescence of corn and soybean crops during that time frame, leading to replenished soil moisture conditions; thus, the resumption of tile flows.

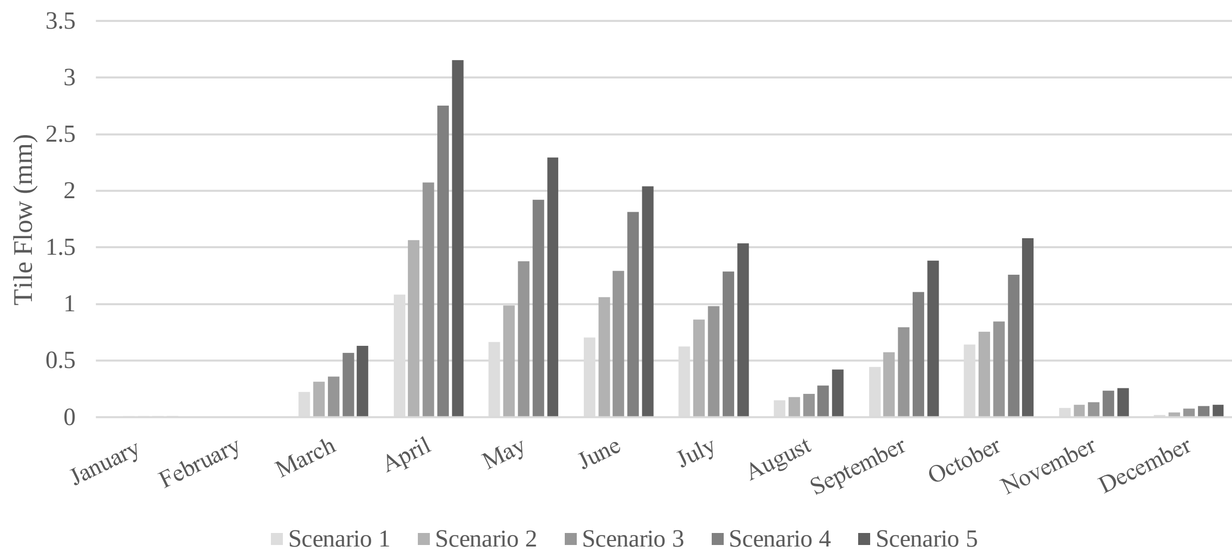

Figure 4: Average tile flow for each month of the year for the 2007-2021 study period for tile drainage scenarios.

The analysis of the impact of tile drainage on downstream flooding suggests that tile flow reduces the total number of flood events (or flood days) across the scenarios. For the baseline scenario, it was found that there were two flood events—March 2019 and September 2019—that produced an action flood stage over the study period. An investigation of the average daily peak flows indicated a total number of 24 flood days (greater than 78.0 m^3/s) during the baseline study period. It is important to note that the March 2019 and September 2019 events were observed flood events and were simulated by the model, hence adding to the validity of the model. All simulated tile drainage scenarios resulted in the same findings (i.e. two flood events in March and September 2019), though the total number of flood events decreased with increasing tile-drained agricultural land (Table 4). From the baseline scenario, with no tile drainage, to Scenario 5, with 75% tile-drained agricultural land, the total number of flood days decreased by 13 days.

Table 4: Total number of flood days for baseline and tile drainage scenarios.

Scenario	Flood Days
Baseline	24
Scenario 1	23
Scenario 2	22
Scenario 3	18
Scenario 4	13
Scenario 5	11

While the results indicate a reduction in flood days due to the implementation of tile drainage, it is important to note the scale of the study. Flooding occurring with the level of tile implementation in this study may be causing flash flood events which are generally noticeable at time step smaller than daily. The analysis conducted in this study focused of daily flood events which did not account for flash flooding. An extension of this study should consider running the scenarios on sub-daily time step to capture these flash flood events which are common in the upper Midwest. It is hope that this study would generate discussions and interests to replicate the approach herein utilized with sub-daily time step for SWAT simulations and various implementation levels of tile drainage scenarios.

SUMMARY AND CONCLUSIONS

A SWAT model was developed for Skunk Creek watershed in southeastern South Dakota to study the potential influence of subsurface tile drainage systems on daily downstream flood events. The model was calibrated and validated using the NSE, PBIAS, and RSR statistics, which demonstrated satisfactory agreement between simulated and observed daily streamflow. The results obtained in this study provide insight into the hydrological response to the installation of subsurface tile drainage in Skunk Creek watershed. A comparison of the average annual water budget between the baseline and tile drainage scenarios indicate a decrease in surface runoff, groundwater flow, deep aquifer recharge, and percolation, while there is an increase in lateral soil flow, tile flow and evapotranspiration.

The overall contribution of average annual tile flow ranged from 4.13% to 15.43% across the five scenarios, and was validated against observed tile flow in a similar watershed. Additionally, the analysis of seasonal variability of tile flow showed that flow occurred from March to October, with little to no tile flow from November to February. The effect of increased tile-drained agricultural land suggests that tile flow seems to reduce the number of daily flood events (flood days) across the studied scenarios.

Given the limitations of the study, the results highlight the need to study scenarios on a sub-daily time-step to capture flash flood events which are common in the upper Midwest. It is hoped that this study would generate further discussions and interests to replicate the approach with a sub-daily time-step for SWAT simulations and various tile drainage scenarios, as the continued development and understanding of the contribution of tile to river discharge and downstream flooding is necessary.

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