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MEMORANDUM

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From: Michelle Schmidt, Jon Butcher

Date: January 2, 2019

Subject: Interflow and Tile Flow Analysis for the Minnesota River Basin

FINAL

Project Number: 100-IWM-T36278.15

This memorandum discusses hydrologic components contributing to streamflow during periods when Total Suspended Solids (TSS) exceeds criterion concentrations in the Minnesota River Basin (MRB). This deliverable is for Objective 2, Task C of *Modeling Support for the Minnesota River Basin Sediment Reduction Strategy Updates*. In Task A, linked Hydrologic Simulation Program Fortran (HSPF) models of MRB watersheds (Tetra Tech, 2016) were used to identify and characterize TSS exceedances for major tributaries to the Minnesota River (Tetra Tech, 2018). The mouths of analyzed tributary streams are classified as type 2B, warm water/cool water, and the Minnesota Water Quality Standard for TSS for type 2B segments specifies a target TSS concentration of ≤ 65 mg/L with an exceedance frequency of ≤ 10% between April - September (https://www.revisor.mn.gov/rules/?id=7050.0222). The main objectives of this task, Task C, build on analyses completed for Task A, and include:

- Characterization of the hydrologic components contributing to streamflow for periods associated with elevated TSS (identified in Task A)
- Estimation of the contribution of tile drain flow to streamflow during TSS exceedance periods
- Examination of the hydrologic impacts and relative importance of storing water in tile drains
- Identification of critical times of the year when tile and non-tile water storage could be most beneficial

A significant fraction of the TSS load in the MRB is believed to be associated with near-channel sources, exacerbated by increasing high flow events. The overarching goal of this work is to assess the relative importance of storing water in tile drainage systems during high flow events as opposed to other water storage options (e.g., surface detention ponds) to reduce channel sources of sediment. Analyses completed for this purpose applied the HUC8-scale HSPF models, an existing Soil and Water Assessment Tool (SWAT; Neitsch et al., 2011) model of the Little Cobb River watershed, and information from related studies.

1.0 BACKGROUND

Tile drainage systems have facilitated crop production in much of the naturally poorly draining MRB. Most of this historically wetland-rich watershed is now utilized for cultivating crops. Draining depressional areas in the watershed to support agriculture has significantly altered the natural hydrologic regime in the basin. Fields with tile drainage (especially when surface inlets are present) can increase quickflow runoff of precipitation that would otherwise be retained on the land surface while also increasing the total amount of precipitation supply that is converted to runoff rather than returning to the atmosphere via evapotranspiration. Research has shown that heavily anthropogenically altered watersheds exhibit up to 50% higher water yields compared to the watershed in its natural state (Schottler et al., 2013).

Schottler et al. state that increased water yields in southern Minnesota are strongly correlated with artificial drainage and loss of depressional areas (although other natural and anthropogenic factors not considered may contribute to increased water yields). A comprehensive literature review on the impacts of artificial drainage on peak watershed flows in the Red River Basin by the Basin Technical and Scientific Advisory Committee (BTSAC) concludes that subsurface drainage systems generally store water and reduce surface flows from fields but consequentially increase the total water output from fields (BTSAC, 2011). The synthesis paper also states that other conditions can vary the flow response on artificially drained fields; for example, cracks in the soil profile during dry periods can speed outflow from tile systems. The BTSAC states that because complex processes are involved, the research on peak flow response due to subsurface drainage is inconclusive (e.g., may vary by inlet type, network layout, capacity), and that research on the impacts at the watershed scale is quite limited as is research on the response difference for storms of varied intensity and duration.

It is not the individual highest peak flows that determine total sediment load but the accumulating effects of flows above a sufficient threshold to mobilize and move sediment. Extreme events can move large quantities of sediment, but, are by their definition, of infrequent occurrence. Ravine incision and bluff toe erosion associated with high flow are significant contributors to the suspended sediment load in the Minnesota River and some of its tributary streams (e.g., Gran et al., 2011). Hydrologic modifications that dampen peak flows or reduce the frequency of flows that are sufficient to cause bank/channel erosion are advantageous in terms of mitigating near-channel sources of sediment. Water stored and released slowly from tile drainage systems or other water storage practices can potentially be beneficial for this reason; however, rapid releases from tile drains with surface inlets may have the opposite effect, while reductions in evapotranspiration loss due to tile drains could also increase the frequency of erosive flow events in streams.. The potential cumulative effect of operating tiles with the objective of storing additional water temporarily during critical periods, however, is uncertain, as is the relative importance of tile water storage versus non-tile water storage (e.g., detention basin, wetland).

We constructed a modeling-based approach to provide further insight into these matters for watershed planning and management. This approach combines information from multiple modeling platforms developed for this region. Calibrated HSPF models provide a robust representation of upland hydrologic processes and streamflow across the MRB. The HSPF model, however, does not explicitly simulate tile drains; rather, artificial drainage is represented as enhanced lateral interflow – an approach originally developed by the U.S. Geological Survey and implemented and tested in the MRB HSPF models. While this approach appears to perform well in practice, it does not clearly distinguish between tile drain flow and natural lateral flow. Therefore, information from other sources was needed to estimate the fraction of interflow from agricultural lands that should be attributed to tile drainage.

In contrast, the more recent versions of SWAT do incorporate explicit tile drain simulations for agricultural land (Neitsch et al., 2011). SWAT is a semi-physically based watershed and crop growth model that was developed by the U.S. Department of Agriculture (USDA) Agricultural Research Service (ARS). A SWAT model that covers the entire MRB is currently under development at the University of Minnesota. We anticipated being able to use this model in support of Objective 2, but it was not available in time for this assessment. Instead, we used a smaller-scale SWAT model of the Little Cobb River watershed (in the Le Sueur River HUC8) to differentiate the fraction of interflow that is tile flow in the HSPF models (Schmidt et al., 2018). Estimated tile density information from a joint study by Minnesota DNR and MPCA was applied to scale unit-area tile flow estimates from HSPF/SWAT to points in the stream network of interest.

2.0 FLOW PATHWAY ASSESSMENT WITH SWAT

Tetra Tech developed a calibrated SWAT model of the Little Cobb River watershed for the U.S. Environmental Protection Agency Office of Research and Development to examine the performance of agricultural best management practices (BMPs) under potential future climate scenarios (Schmidt et al., 2018). The Little Cobb River watershed SWAT model simulates plant growth, field management operations (e.g., tillage), and cropland with and without tile drains. We modified the SWAT 2012 FORTRAN code to provide separate output for tile flow, which is by default combined with soil lateral flow.

The SWAT model achieves a good fit to observed hydrology and is an appropriate tool for assessing flow pathways on cropland in this region. Information from the Little Cobb River SWAT model is applicable to this study of the greater MRB because corn and soybean are the crops represented in the SWAT model, as well as associated management practices, and these are the main crops cultivated across much of the MRB. In addition, the SWAT model represents diverse soils from well-draining sandy soils to poorly draining clay soils and varied slope classes (< 3%, 3-10%, >10%) that are present across the MRB.

The Hooghoudt and Kirkham method is implemented in the Little Cobb River SWAT model to simulate drainage, soil and tile water storage, and release from tile systems as a function of tile depth, spacing, and inlet characteristics (Moriasi et al., 2013). Cropland on naturally poorly drained soils (soils classified as Hydrologic Soil Groups D, A/D, B/D, or C/D, and on low slopes ranging from 0 – 3%) were represented as having tile drainage systems. The dominant cash crops in this are corn and soybeans, and producers typically rotate between these two. Corn-soybean rotations and associated practices, including soil cultivation, tillage, and fertilization, are represented in the model.

Hydrologic pathways of tiled and non-tiled fields were assessed with the Little Cobb River watershed SWAT model for the period of 2002-2015. The pathways represented in the model include surface runoff, shallow lateral flow, tile flow, and shallow groundwater discharge. Annual average flows simulated by the SWAT model are presented by pathway for tiled and non-tiled cropland in Figure 2-1. Non-tiled fields exhibit higher surface runoff (about 40% of total flow) in the SWAT model. Runoff is a smaller contributor where overland flow is rerouted to tile lines (approximately 9%), and tile flow is shown to be the dominant flow pathway (about 60%). Soils on non-tiled fields better infiltrate rainwater, naturally recharging shallow groundwater that contributes to streamflow. The contribution from surficial groundwater is lower on artificially drained fields because some infiltrating water is intercepted by the tile lines. About 97% of interflow on cropland with artificial drainage is tile flow and 3% is shallow lateral flow (Figure 2-2). The flow pathways on tile versus non-tiled fields differ significantly; however, the total annual flow is nearly equivalent, only 2.5% lower for tiled fields.

Surface runoff and subsurface tile flow data were available by Water Year (WY) from a 26.2-acre Discovery Farms core research site (BE1) in the Le Sueur watershed, Blue Earth County, Minnesota (S. Matteson, personal communication, May 2018). Corn and soybeans are cultivated on this research catchment that is comprised of poorly draining silty clay loam soils with artificial drainage. Total flow was divided into surface runoff and subsurface tile flow (i.e., groundwater discharge not included). Subsurface tile flow fractions ranged from 43% in WY 2013 to 89% in WY 2012 at this site and averaged 77% from WY 2012-WY 2016 (Figure 2-3). Surface runoff and subsurface tile flow data were also available for WY2017 for two Discovery Farm sites in the Redwood watershed (RW1S and RW1N). Both study catchments are used to cultivate corn and soybeans. Approximately 89% and 98% of flow was through subsurface tiles at site RW1N and RW1S, respectively. A similar assessment was completed for the Little Cobb River SWAT model using surface runoff and shallow interflow (almost all being tile flow). Results from the SWAT model were comparable to BE1, averaging 84% from 2002-2015. Note that to provide a suitable comparison to the Discovery Farms sites that don't monitor baseflow (and are likely relatively small waterways that are not fed by resurfacing groundwater), groundwater contributions were not included in this tabulation. Groundwater produces about 30% of the total flow leaving tiled fields in the SWAT model and is therefore a key component of the overall water balance at the watershed scale. The respective contribution of tile flow is lower (about 58%) when groundwater is considered on artificially drained fields.

Flow pathways in the SWAT model were also assessed by Hydrologic Soils Group (HSG). The distributed SWAT model represents single (A through D) and dual soil classifications. As previously mentioned, poorly draining D soils and associated dual classes (e.g., B/D), are simulated as being tile drained. Flow pathways are shown for non-tiled cropland by HSG in Figure 2-4, and for tiled cropland in Figure 2-5. Flow pathways differentiated by HSG are comparable to those shown in Figure 2-1. The lateral flow component is minor for all soil types on non-tiled fields, and surface runoff and groundwater discharges are the primary contributors to streamflow. On drained fields, however, tile flow is the dominant component, and little flow reaches the stream via overland runoff.

The SWAT model was also used to characterize differences in the magnitude and timing of flows on tiled and non-tiled fields. Two simulated storm events are provided as an example; a September 2015 storm event is shown in Figure 2-6, and a June-July 2014 storm event is shown in Figure 2-7.

On non-tiled fields surface runoff exhibits the maximum, and earliest peak flow for both storms. As surface flow recedes, delayed contributions from groundwater on non-tiled fields rises. Very little flow is transmitted as shallow subsurface lateral flow on non-tiled fields for soils and slopes present in the Little Cobb watershed. Flow dynamics are quite different from tiled fields. Peak flows on fields with tile drainage are delayed and never reach the magnitude exhibited on non-tiled fields. This is consistent with findings from the Discovery Farms monitoring program (Discovery Farms, 2016); flows on tiled fields are less intense but more frequent (195 days per year of flow at an average intensity of 0.03 in/d) compared to non-tiled fields (10 days per year of flow at an average intensity of 0.38). Model results show tile systems extend field outflow over a longer period and generate lower total flow for these example storm events.

Flow responses differ for these two storms due to antecedent moisture conditions. Antecedent moisture was higher for the September storm. Precipitation over the month and week leading up to the September 2015 event was 168 mm and 21 mm, whereas these were 78 mm and 6 mm for the 2014 summer storm. Drier background conditions facilitate quick infiltration of precipitation, and more streamflow comes from groundwater discharge during the 2014 event compared to the 2015 event.

Prior to being converted to productive agricultural fields, depressional wetlands that were likely partially or fully disconnected from the stream network spanned the MRB. Therefore, tiled and non-tiled cropland both generate quicker storm flow responses compared to the natural landscape. The examples provided in Figure 2-6 and Figure 2-7 indicate that following storm events flows from passively tiled fields are less intense, and prolonged compared to non-tiled fields – in large part because non-tiled fields have better natural drainage. Nevertheless, modifications to tile drainage systems can potentially further dampen damaging peak flows during critical periods. For example, adjustable weirs or flashboards could be installed at outlets and operated to control tile outflows (i.e. controlled drainage).

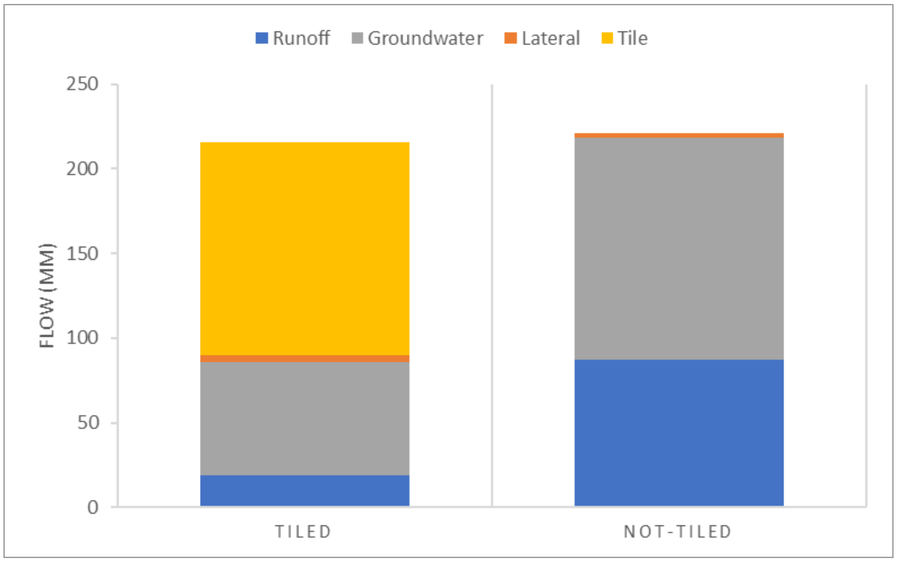

Figure 2-1. Average Annual Flow by Pathway for Tiled and Non-tiled Corn and Soybean Fields in the Little Cobb River SWAT Model

Note: “Runoff” refers to direct overland flow. “Lateral” refers to interflow to stream via shallow soil pathways.

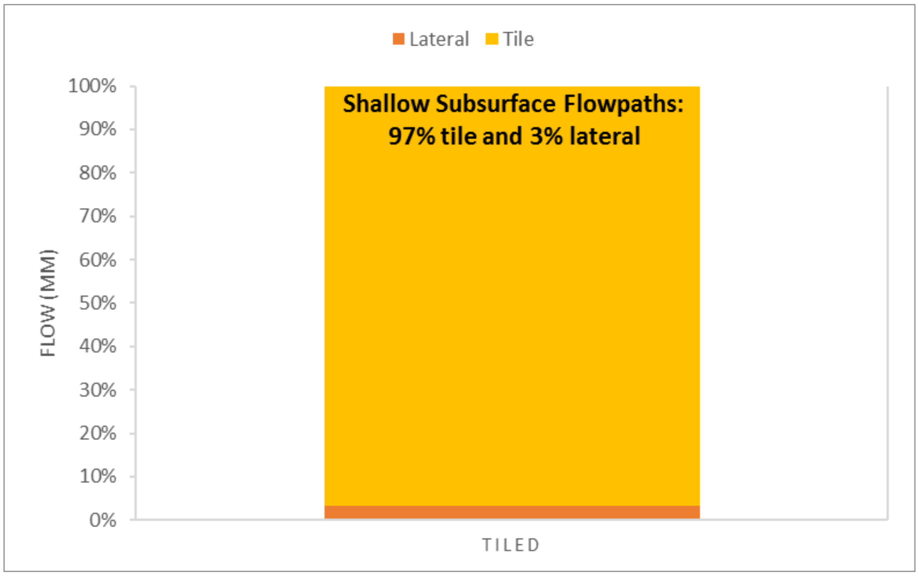

Figure 2-2. Lateral and Tile Fractions of Flow on Tiled Cropland in the Little Cobb River SWAT Model

Note: “Runoff” refers to direct overland flow. “Lateral” refers to interflow to stream via shallow soil pathways.

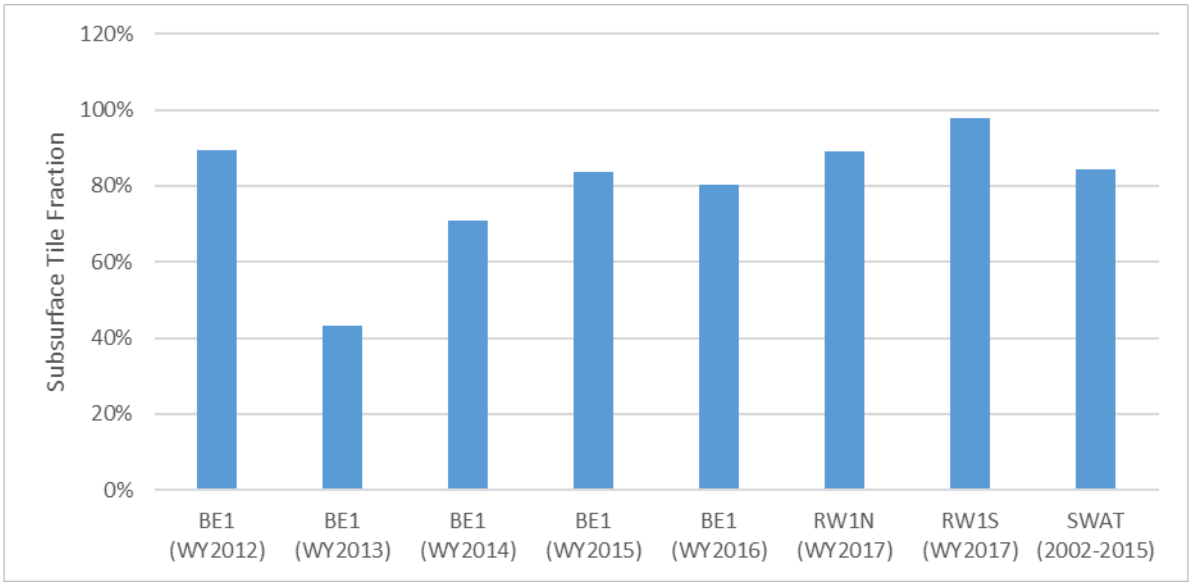

Figure 2-3. Subsurface Tile Fraction of Flow (Tile + Surface Runoff) for the Blue Earth (BE1) Discovery Farms Research Site and Little Cobb River SWAT Model

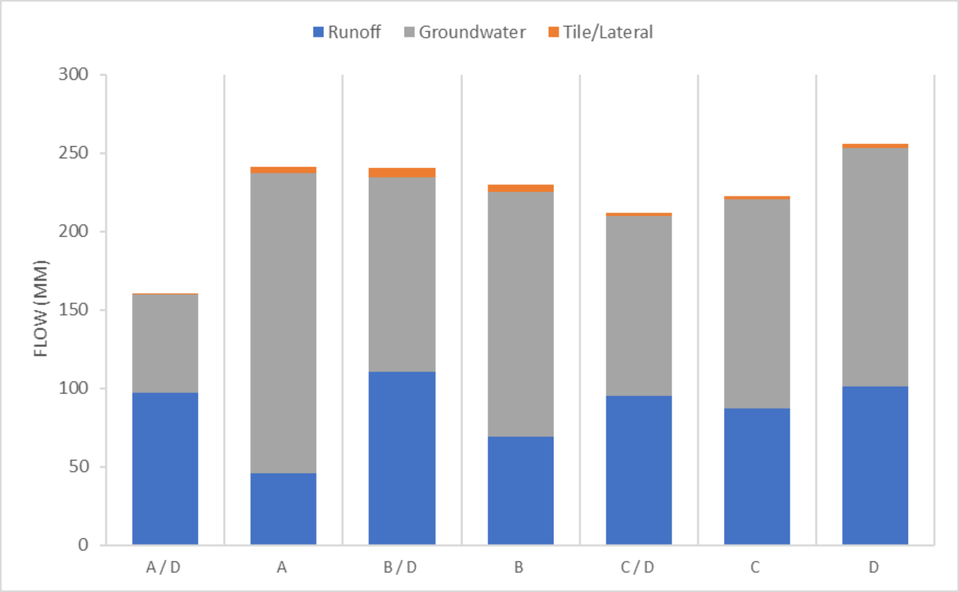

Figure 2-4. Average Annual Flow by Pathway and Hydrologic Soil Group (HSG) for Non-tiled Corn and Soybean Fields in the Little Cobb River SWAT Model

Note: “Runoff” refers to direct overland flow. “Lateral” refers to interflow to stream via shallow soil pathways.

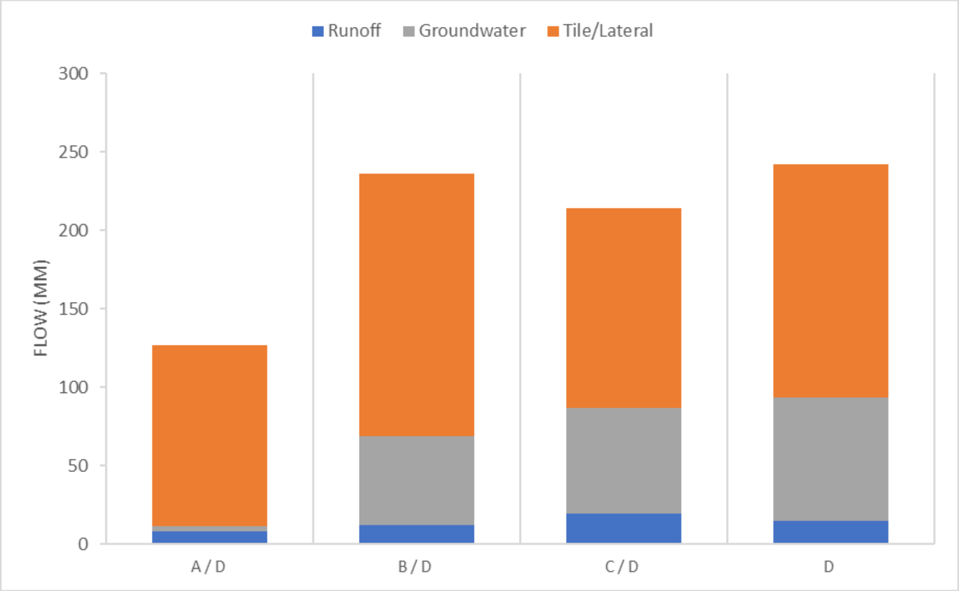

Figure 2-5. Average Annual Flow by Pathway and Hydrologic Soil Group (HSG) for Tiled Corn and Soybean Fields in the Little Cobb River SWAT Model

Note: “Runoff” refers to direct overland flow. “Lateral” refers to interflow to stream via shallow soil pathways.

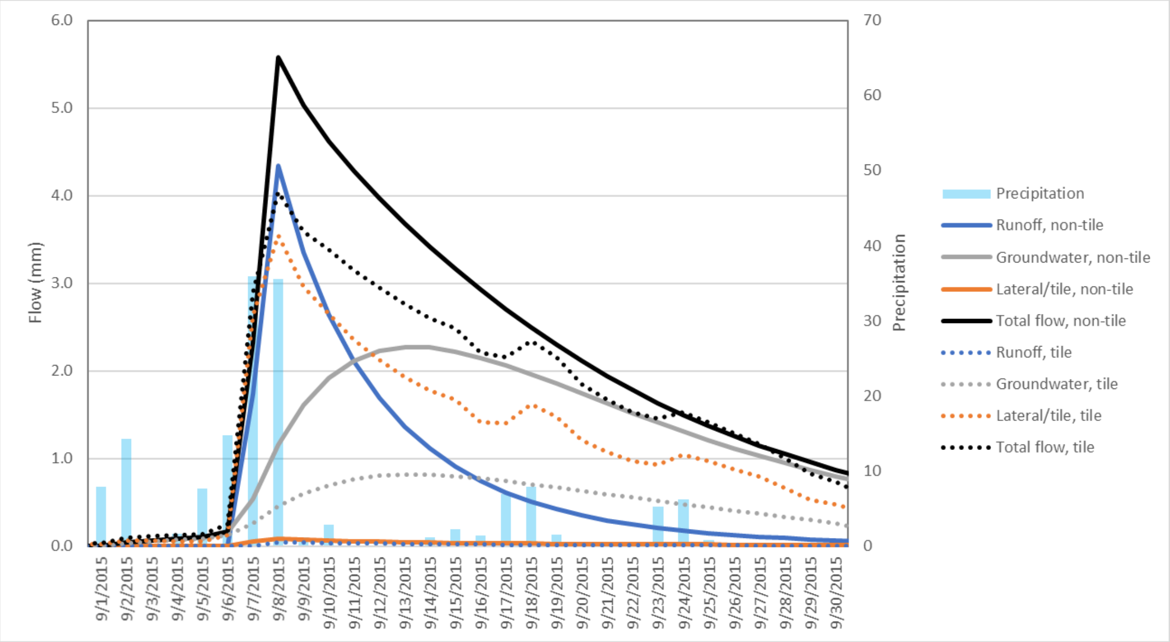

Figure 2-6. Upland Flow (mm) by Pathway for Tiled and Non-tiled Cropland in the Little Cobb River SWAT Model, September 2015

Note: “Runoff” refers to direct overland flow. “Lateral” refers to interflow to stream via shallow soil pathways Total precipitation over the previous month (8/20/2015-9/20/2015) was 168 mm, and over the previous week 21 mm.

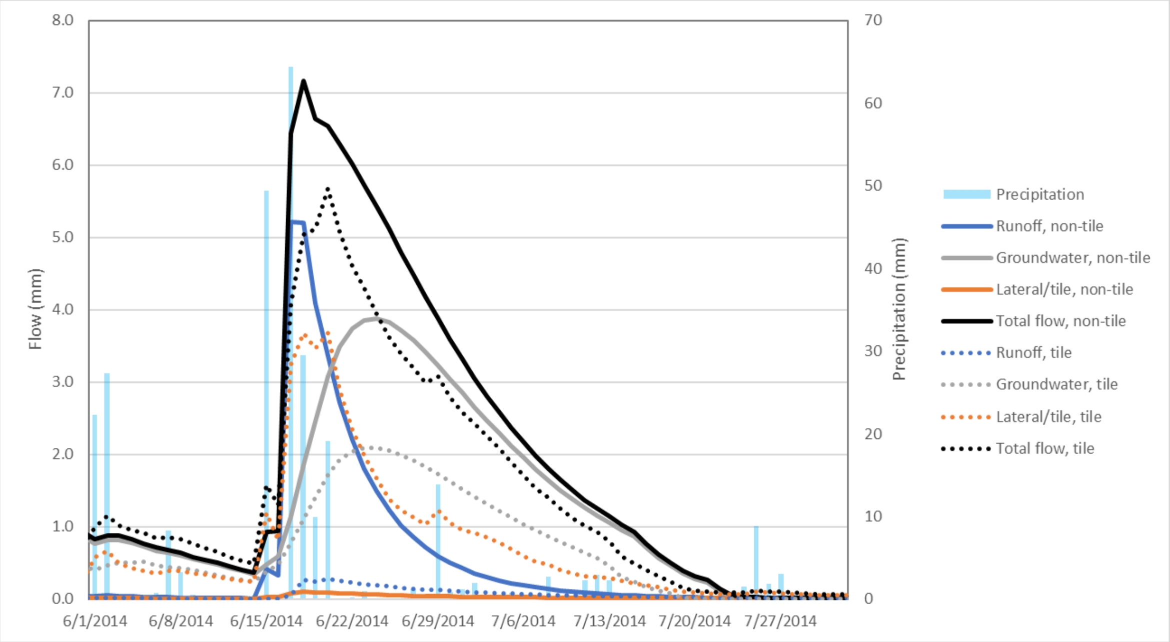

Figure 2-7. Upland Flow (mm) by Pathway for Tiled and Non-tiled Cropland in the Little Cobb River SWAT Model, June-July, 2014

Note: "Runoff" refers to direct overland flow. "Lateral" refers to interflow to stream via shallow soil pathways. Total precipitation over the previous month (5/1/2014-5/31/2014) was 78 mm, and over the previous week 6 mm.

3.0 ESTIMATION OF TILE DRAIN FLOW CONTRIBUTIONS

Linked HSPF HUC8-scale models in the MRB were used to estimate the relative contribution of tile flow to streamflow during TSS exceedance periods. The HSPF models do not contain routines for the explicit representation of tile drains, and tile versus non-tile fields are not differentiated for cropland. Rather, interflow in the HSPF models includes both shallow subsurface lateral and tile flow, and interflow was calibrated to represent the net effect of enhanced subsurface tile drainage in these watersheds, based on the distribution of HSGs and slopes, as discussed in Tetra Tech, 2009. Nevertheless, the HSPF models are useful for assessing the relative importance of water storage options because flows contributing to TSS exceedances can be traced back to different land uses and pathways throughout the MRB. Information from HSPF, SWAT, and from tile mapping studies in the MRB were combined to analyze the fraction of HSPF interflow attributed to tile flow as follows:

HSPF: TSS exceedances previously identified for HUC8 and select HUC10 watersheds using the HSPF models were applied for this assessment (Tetra Tech, 2018). Area-weighted unit interflow (inches/time) from cropland that contributes to streamflow during TSS exceedance periods was computed based on the HSPF models.

SWAT: The estimate of tile (97%) versus non-tile (3%) interflow derived from the Little Cobb River watershed SWAT was applied to distinguish the tile component of interflow in the HSPF models. (A larger-scale SWAT model of the MRB is not yet available at the time of this work to characterize spatial differences in interflow components.) It is reasonable to assume that most interflow is intercepted by tile lines where artificial drainage systems are present, as is indicated by the SWAT model. Thus, the fraction of interflow that is assumed to be tile flow was applied uniformly across the MRB for this analysis.

Tile Mapping Studies: Minnesota DNR and MPCA estimated tile drainage densities for catchments in Minnesota in GIS based on soil, slope, and crop data (Wall et al., 2017, https://mrbdc.mnsu.edu/sites/mrbdc.mnsu.edu/files/public/org/tile/reinventory.html; MGWA, 2018, http://www.mgwa.org/documents/whitepapers/Drain_Tiles_and_Groundwater_Resources.pdf). Nine different tile drainage density prediction models were tested that used different combinations of soil (HSG), land slope, and crop information (e.g., less than 3% slope and Hydrologic Soil Group). Estimates from the nine models were compared to tile drainage densities established from installation permits, aerial imagery, and information provided by producers. As discussed by Wall et al. (2017), the hydric class and less than 3% slope model proved to be a strong predictor of tile drainage that was not as biased as the HSG based models. Therefore, a spatial binary grid indicating the presence or absence of tile lines from the recommended model (hydric class and slope < 3%) tile presence predictor model, (titled: tde_lt3prct_hydclprs.tif, resolution of 30m) was applied for this assessment (grid provided by B. Gosack, personal communication, August 2018). Estimated tile drained cropland was tabulated for each study catchment. The percent of each catchment estimated to drain to tile systems is presented in Table 3-1.

Table 3-1. Percent of Land Estimated to Drain to Tile Lines

HUC8 Watershed	Tile Drained Cropland Area (sq. mi)	Percent of Watershed Estimated to be Tile Drained
Yellow Medicine	157	23%
Hawk Creek	123	24%
Hawk-Yellow Medicine	602	29%
Chippewa	236	11%
Redwood	200	29%
Cottonwood	443	34%
Blue Earth below Watonwan and Le Sueur	1,524	43%
Blue Earth above Watonwan and Le Sueur	660	43%
Watonwan	373	43%
Le Sueur	488	44%

Derived from a grid showing estimated locations of tile drainage systems based on hydric class and less than 3% slope (B. Gosack, personal communication, August 2018; 30 m resolution binary grid titled tde_lt3prct_hydclprs.tif)

Total daily tile flow during TSS exceedance periods was estimated as:

$$T = I_{crop} \times f_{tile} \times A \times a_{tile}$$

where T is the total tile flow contributing to streamflow in AF/d; I_{crop} is the area-weighted unit interflow from cropland in in/d; f_{tile} is the fraction of interflow that is tile flow based on the Little Cobb River SWAT model (uniformly 97%); A is the total contributing drainage area in acres; and a_{tile} is the percent of the watershed estimated to drain to tile lines (Table 3-1).

The average streamflow from tile flow and total streamflow for days when simulations showed TSS exceeded the 65 mg/L target are presented by month and watershed in Figure 3-1 through Figure 3-8. In these figures, average streamflow includes flow derived from surface runoff, interflow (lateral non-tile and tile flow) and groundwater discharge that originates from tiled and non-tiled cropland as well as from other land uses in the drainage area, and direct precipitation to stream reaches. These figures provide information on the fraction of streamflow that is from upland tile flow. About 44% of land in the Le Sueur watershed is tiled cropland; however, the percentage of monthly streamflow from tile systems averages 20% from April – September because some precipitation on tiled fields contributes to streamflow via non-tile flow pathways (primarily shallow groundwater). As discussed in Section 2.0, 58% of the water leaving tiled fields in the SWAT model is through tile lines. (This roughly equates to 26% of total streamflow at the watershed scale (44% of land x 58% of flow) on average, which varies by storm based on antecedent conditions. In addition, the proportion of streamflow from tile lines is slightly lower than this rough estimate because some streamflow comes from direct precipitation to the water surface). The relative importance of storing tile drainage water as compared to other non-tile water is shown by month in each of these figures (i.e., tile drainage storage is more important in months with high overall flows and a high fraction of the flow coming from tile drainage systems). These figures also show times of year when total flow volume for days with TSS excursions is largest, generally in the early fall for the studied catchments.

This analysis focused on the lower MRB where tile drainage is most dense (e.g., Le Sueur and Watonwan). Estimates were also generated for Hawk Creek, Yellow Medicine River, and Cottonwood River to examine the upper MRB where tile drainage density tends to be lower. Estimates of tile flow contribution to the mainstem were not assessed because benefits achieved through water storage in HUC8 watersheds will translate to improvements in the mainstem Minnesota River. Furthermore, regions to target for tile water storage management are identifiable with the HUC8-scale assessments.

Tile flow contributions during TSS excursion events vary across the studied watersheds, mainly due differences in estimated tile density. Except for September in the Watonwan watershed, less than 20% of streamflow for TSS excursion events is attributed to tile drains. The rest of streamflow in Watonwan is conveyed as surface runoff, non-tile lateral flow, and groundwater discharge. In late spring to early summer tile flow contributions are shown to be about 22% in the Le Sueur River watershed. GSSHA modeling (Gridded Surface Subsurface Hydrologic Analysis) that explicitly simulates tile drainage systems has been conducted for Seven Mile Creek, which is in the Middle Minnesota watershed and directly adjacent to the Le Sueur River watershed (Downer et al., 2014). GSSHA results indicate that that approximately 40% streamflow in the late spring and early summer comes from tile flow in this watershed, which is higher than results from this dual HSPF/SWAT study, potentially due to the specific characteristics of the much smaller-scale study area.

Most flow is non-tile in the Hawk Creek and Yellow Medicine watersheds. Therefore, other water storage opportunities have more potential for mitigating high flows. Results across the study areas indicate that tile flow (or other) storage would be most critical in the spring (April) and fall (September) when high flows occur more frequently. Research on Discovery Farms core sites indicates that the typical timing of most tile flow is in the early spring through summer (Discovery Farms, 2018). Summer months tend to be drier. The water table drops over the summer, and tile systems are likely to be at low capacity by early fall. Therefore, when fall storms occur a larger than usual fraction of precipitation is routed via tile lines. This could be a potentially advantageous period to make use of tile water storage; however, implications for crop harvesting operations would need to be considered.

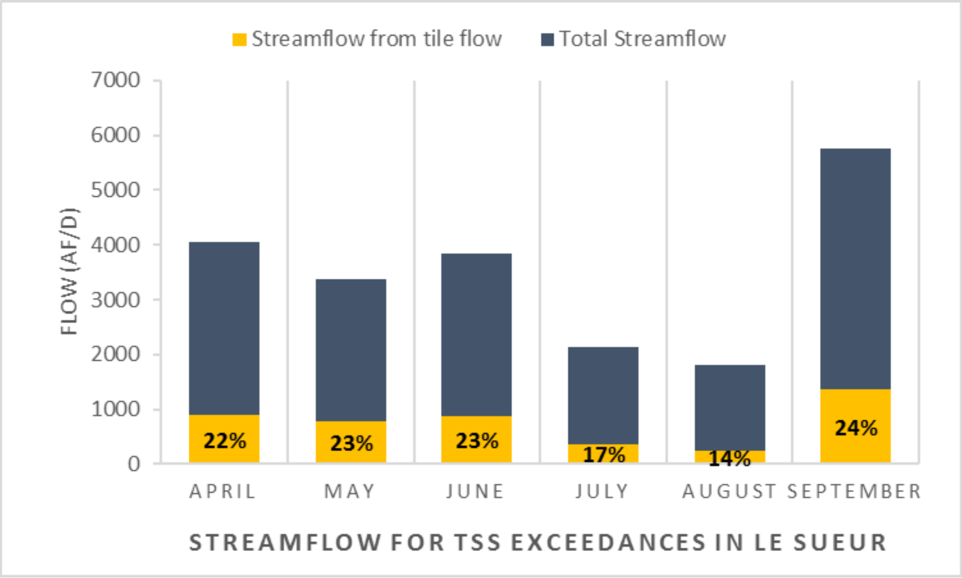

Figure 3-1. Average Streamflow from Tile Flow and Total Streamflow for TSS Exceedance Periods in the Le Sueur River Watershed HSPF Model (R850)

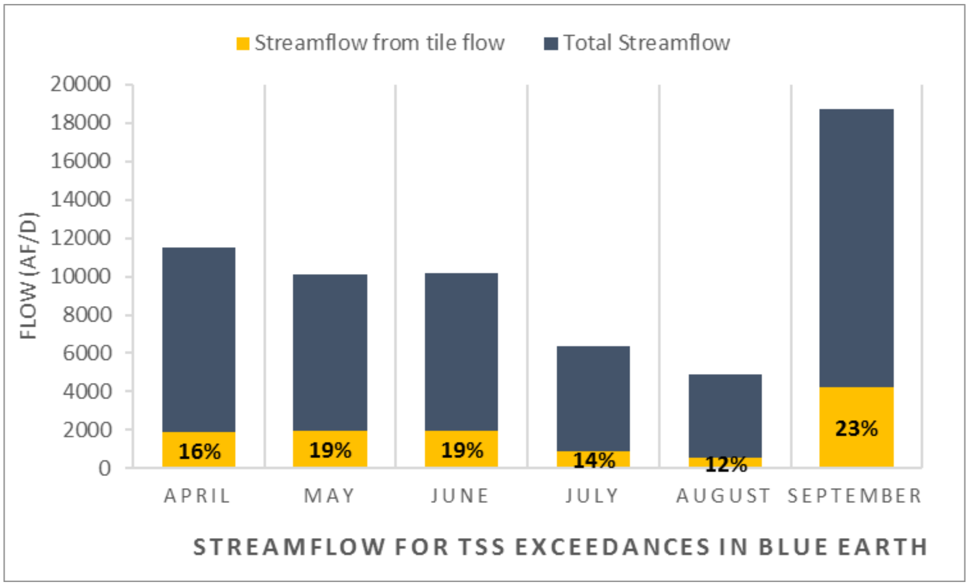

Figure 3-2. Average Streamflow from Tile Flow and Total Streamflow for TSS Exceedance Periods in the Blue Earth River Watershed HSPF Model (R870, below Watonwan and Le Sueur)

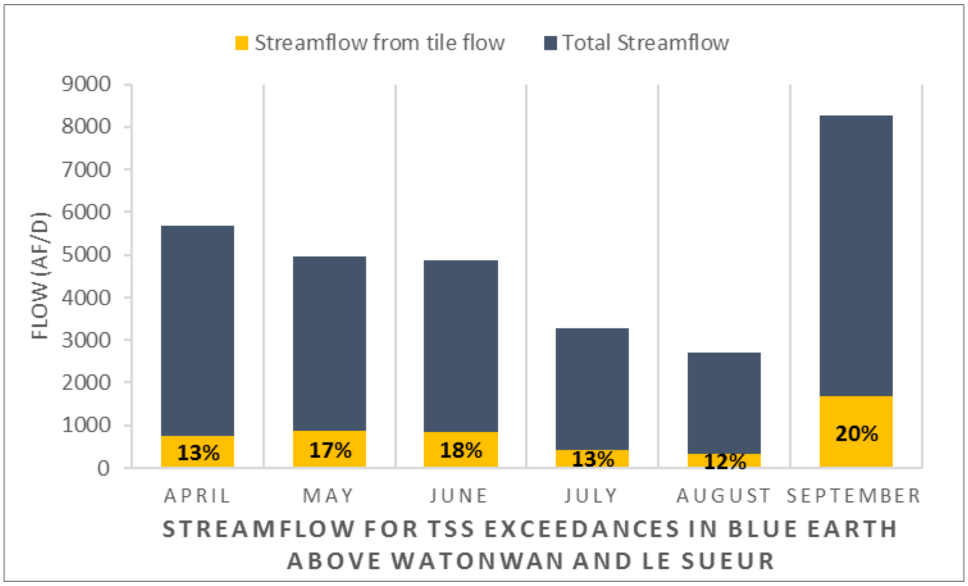

Figure 3-3. Average Streamflow from Tile Flow and Total Streamflow for TSS Exceedance Periods in the Blue Earth River Watershed HSPF Model (R390, above Watonwan and Le Sueur)

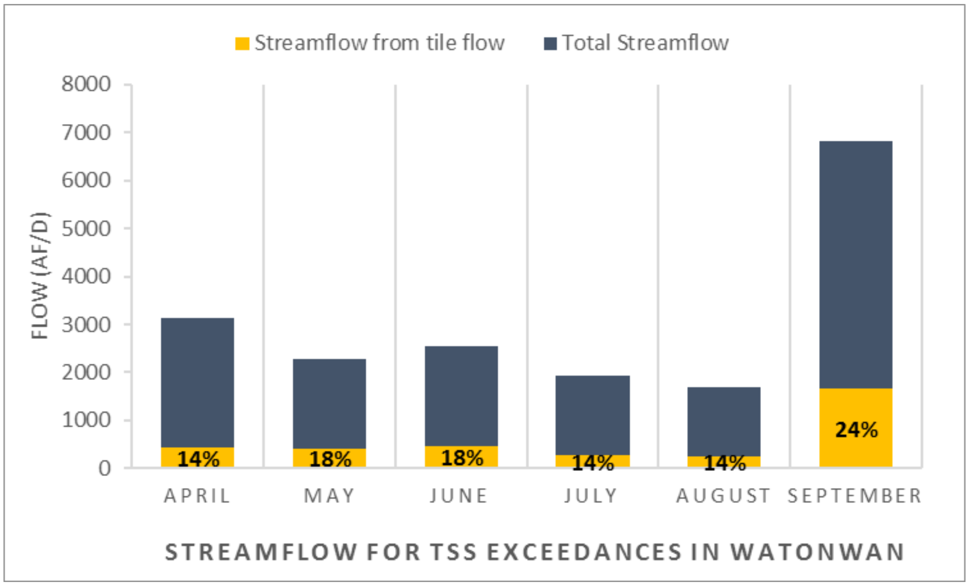

Figure 3-4. Average Streamflow from Tile Flow and Total Streamflow for TSS Exceedance Periods in the Watonwan Watershed HSPF Model (R310)

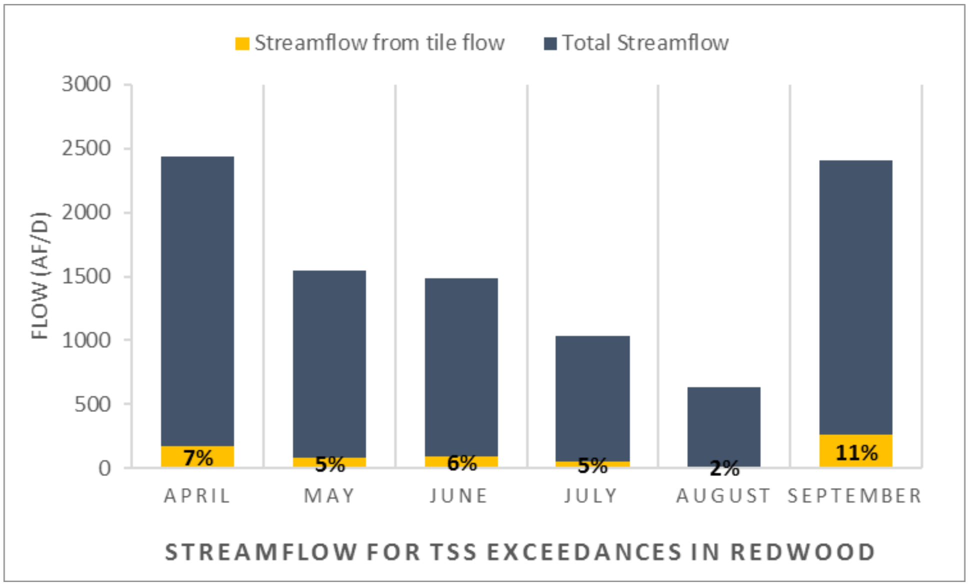

Figure 3-5. Average Streamflow from Tile Flow and Total Streamflow for TSS Exceedance Periods in the Redwood Watershed HSPF Model (R510)

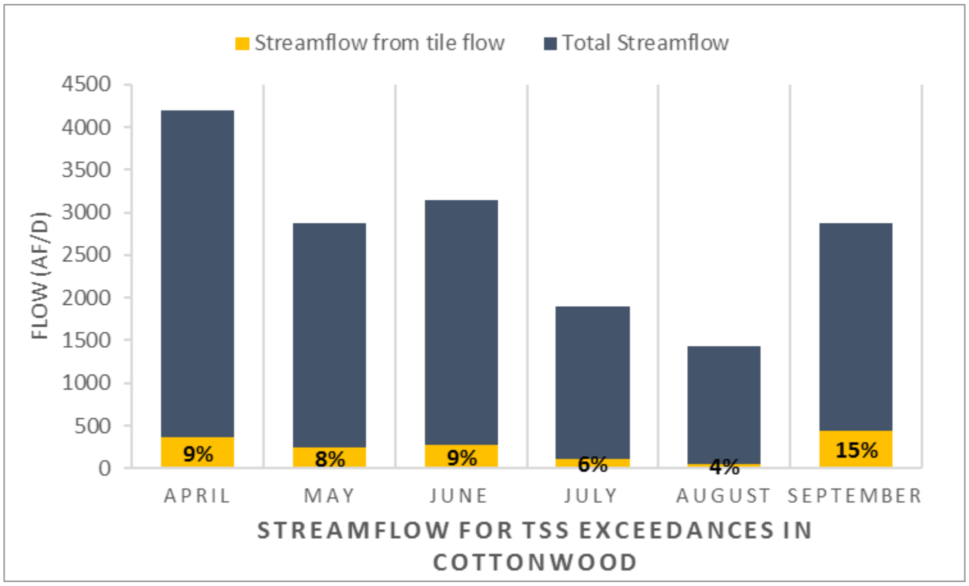

Figure 3-6. Average Streamflow from Tile Flow and Total Streamflow for TSS Exceedance Periods in the Cottonwood Watershed HSPF Model (R490)

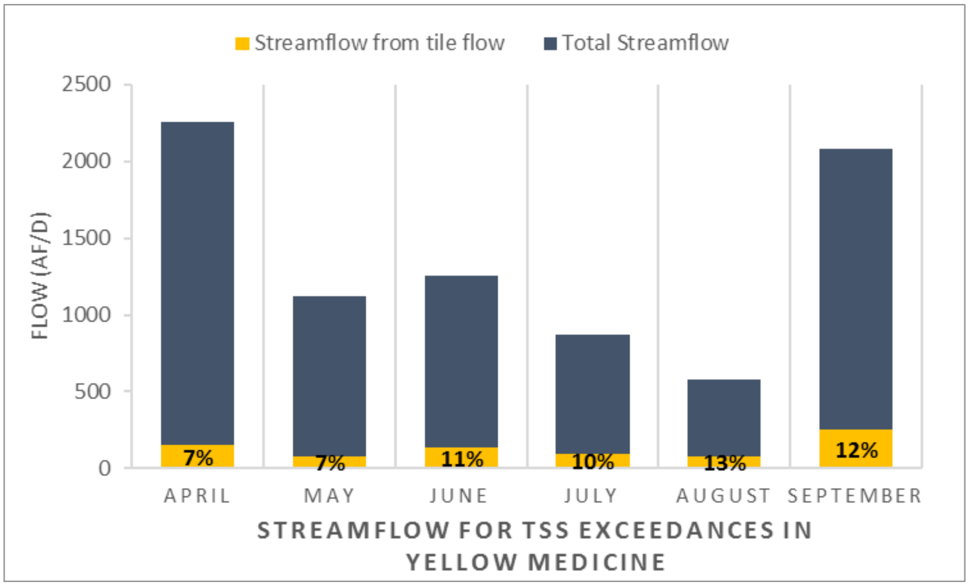

Figure 3-7. Average Streamflow from Tile Flow and Total Streamflow for TSS Exceedance Periods for Yellow Medicine in the Hawk-Yellow Medicine Watershed HSPF Model (R100)

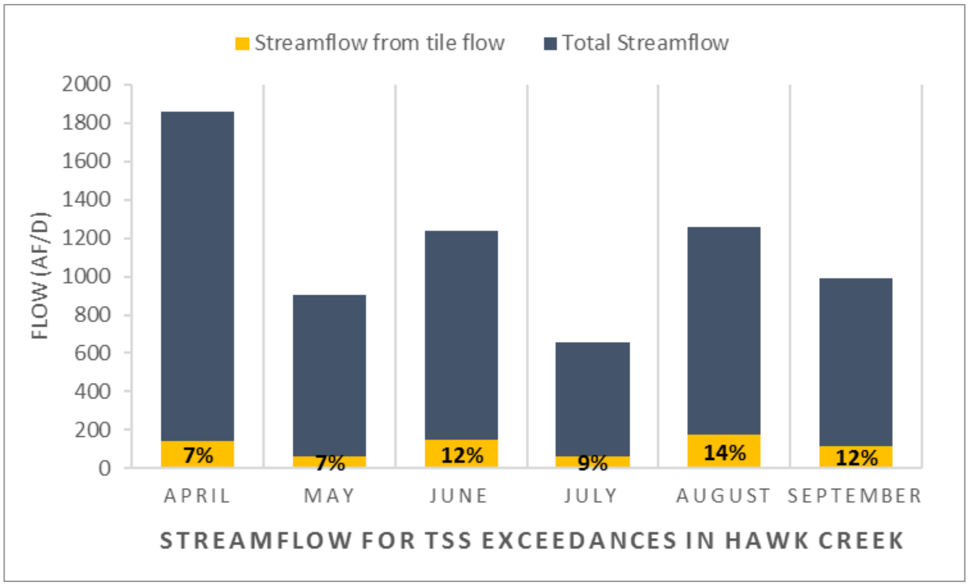

Figure 3-8. Average Streamflow from Tile Flow and Total Streamflow for TSS Exceedance Periods for Hawk Creek in the Hawk-Yellow Medicine Watershed HSPF Model (R201)

4.0 REFERENCES

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