

**MODELING HYDROLOGIC RESPONSE OF CONVERTING  
ANNUAL CROPS TO AGROFORESTRY  
AND OTHER PERENNIAL CROPPING SYSTEMS:  
AN ASSESSMENT OF SWAT AND HSPF CAPABILITIES**

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**ABSTRACT**

Wetland drainage and the widespread conversion from perennial vegetated landscapes to intensive agricultural cropping are principal contributors to the degradation of the Minnesota River and its high sediment and nutrient loads. Pressures to meet Total Maximum Daily Load (TMDL) requirements and to lessen contributions to hypoxia in the Gulf of Mexico suggest that changes in agricultural land use are needed. However, farming in the Minnesota River Basin (MRB) is profitable and any change requires that there be viable economic alternatives for landowners. This ongoing project is investigating agroforestry and other perennial cropping systems as alternatives to current corn-soybean farming that can improve water quality and lead to greater hydrologic stability. Determining changes in streamflow volumes and flow regimes caused by converting annual crops to agroforestry and other perennial crops is the focus of this research which combines field studies with hydrologic modeling. Field plots and small watersheds are being monitored to characterize hydrologic responses of different crops to snowmelt and rainfall regimes. The results of this field research are being used to develop and test model parameters that will enable us to simulate watershed responses to changes in cropping practices. We describe key hydrologic relationships that would need to be represented in any hydrologic model capable of predicting the hydrologic effects of changing annual to perennial vegetation. These relationships are contrasted to model capabilities of the Soil and Water Assessment Tool 2000 (SWAT) and the Hydrologic Simulation Program-Fortran (HSPF) models.

**Keywords:** agroforestry, hydrologic modeling, HSFP, perennial crops, SWAT

**INTRODUCTION**

Hydrologic changes in the Minnesota River Basin (MRB) have resulted from loss of wetlands, agricultural drainage, and conversion from native perennial vegetation to annual crops. The cumulative effects of these land-use changes include increases in soil and nutrient loss, increased runoff and volumes of streamflow, and an overall decline of water quality (Leach et al. 1992). As a result, the MRB has become one of the most endangered waterways in the United States (American Rivers Council 1997).

Meeting Total Maximum Daily Load (TMDL) requirements and reducing contributions from the MRB to hypoxia in the Gulf of Mexico suggest that changes in agricultural land use are needed. However, farming in the MRB is profitable and any change requires that there be viable economic alternatives for landowners. This ongoing project is investigating agroforestry and other perennial cropping systems as alternatives to current corn-soybean farming that can improve water quality and lead to greater hydrologic stability. Beneficial changes in streamflow volumes, flow regimes, and water quality are possible by returning more perennial vegetation to the basin. To assess the hydrologic and water quality implications for the MRB, however, we need to consider how much watershed area can potentially undergo changes in cropping practices, and in what landscape positions will such changes be most beneficial. By taking a modeling approach, we will simulate the hydrologic changes in the MRB that accompany conversions from annual crops to agroforestry and other perennial cropping systems. Two models are considered in this evaluation: (1) the Soil and Water Assessment Tool (SWAT) version 2000, and (2) the Hydrologic Simulation Program-Fortran (HSPF) models. The utility of these models to simulate and compare streamflow response from different perennial and annual crops, including hybrid poplar, willow, and hazelnut to the traditional corn and soybean rotation is the focus of this paper.

### **SIMULATING CHANGES IN VEGETATIVE COVER**

Hydrologic models have proliferated in recent decades, but few have been developed to specifically address the questions posed in this research. Selecting a model to simulate land-use changes that include conversion from annual crops to woody and other perennials, should be based on model design, capabilities, and data requirements. In our case, a deterministic, continuous simulation model is desired that can simulate flow response, nutrient loading, and sediment export from fields and wetlands, to small watersheds, to major watersheds in the MRB. The hydrologic model must be capable of simulating hydrologic processes that relate to particular soil-plant systems. However, data requirements for a model must be compatible with data sets that are available in the MRB.

Key hydrologic processes to be represented in a model capable of simulating vegetative and related land-use changes include: interception, transpiration, total evapotranspiration, rooting depth, soil water depletion, infiltration, surface runoff, subsurface flow (interflow), and soil frost. Snowmelt and soil frost play critical roles in determining spring streamflow in the MRB, and need to be simulated by a model for the basin. The above processes are being evaluated from runoff and drainage plots that contain perennial and corn-soybean crops. These data will be used to help develop parameters and relationships for the model or models selected. A brief discussion of these key hydrologic processes is presented in the following.

(1) Interception: Woody and herbaceous perennial plants would be expected to have higher annual interception losses than annual crops. Functions of changing vegetative leaf area and/or storage over time would be needed to simulate interception.

(2) Transpiration: Woody crops usually are deeper rooted and perennial species, in general, are physiologically active for more days per year than annual crops. Native trees, hybrid poplar, willow, hybrid hazelnuts, and alfalfa are physiologically active earlier in the spring and later in the fall than annuals. This results in greater seasonal ET and consumptive water use over the growing season. Transpiration of annual crops like corn and soybeans does not become significant until late June—early July and diminishes when crops mature. As a result, antecedent soil moisture is expected to differ among annual and perennial crops, particularly early and late in the growing season. In all situations, transpiration is limited by available soil moisture and energy for evaporation, key relationships for any hydrologic model.

(3) Infiltration and soil frost: Trees and other perennial crops can promote higher infiltration rates than annual crops without artificial drainage. In the MRB, antecedent soil moisture in the fall affects the type of soil frost; wet soils promote concrete frost while dry soils experience more granular type frost. Consequently, soil frost conditions affect the proportion of snowmelt that infiltrates or runs off the soil surface in the spring. Woody and other perennial crops and crop residues on the landscape further affect snow deposition, which also influences depth and type of soil frost (US Army Corps of Engineers 1956; Christophersen 2001; Brooks et al. 2003).

(4) Soil moisture depletion: The rooting systems of perennial species are also more complex than those of annual species. Perennials have a root system that remains intact over the winter and is prepared when abiotic conditions allow for growth in the spring (Elowson 1999). An established root system in the spring allows perennials one more advantage over annuals for starting biological activity in the spring.

(5) Artificial drainage: Areas that are converted from annual corn-soybean crops to most perennial crops will no longer require the extensive networks of artificial subsurface drainage and open ditches that are prevalent in the MRB today. This is viewed as a positive hydrologic benefit that can restore lost storage to the landscape and thereby reduce streamflow discharge (Miller 1999).

The applicability of two widely used hydrologic models for this research are described and evaluated below.

### **SOIL AND WATER ASSESSMENT TOOL (SWAT)**

SWAT is characterized as a continuous model that operates on a daily time step. It was developed to quantify the impact of land management practices in large, agricultural watersheds. SWAT was developed to allow the user to predict the effect of alternative land management decisions on water, sediment, nutrient, and pesticide yields with reasonable accuracy on large, ungaged river basins (Neitsch et al. 2002). Because this model was developed for agricultural watersheds in the southern United States, parameters must to be examined and modified to meet conditions in the north central region.

The fundamental hydrology in SWAT is based on the water balance equation:

$$SW_t = SW + \sum_{i=1}^t (R_i - Q_i - ET_i - P_i - QR_i)$$

Where  $SW_t$  is the soil water content at time  $t$  and  $SW$  is the initial soil water content, both given in units of mm minus the 15 bar water content;  $t$  is time (days),  $R$  is daily precipitation (mm),  $Q$  is daily runoff (mm),  $ET$  is daily evapotranspiration (mm),  $P$  is daily percolation (mm), and  $QR$  is a variable that predicts flow through each soil layer in the rooting zone. If the soil temperature in any layer is less than  $0^\circ\text{C}$ , no percolation occurs in the layer. Daily runoff is estimated using the USDA-Soil Conservation Service (SCS) curve number method, in which snowmelt is treated in the same way as rainfall. Channel routing is determined with the Muskingum method. The watershed is divided into subbasins to reflect variations in  $ET$  in different land cover and soil types. Using this method of modeling, runoff is calculated separately in each subbasin and then routed to determine total runoff in the watershed (Arnold et al. 1998).

Input crop parameters for more common crops have been developed for SWAT and are provided in land cover databases (SWAT 2000 User Manual). SWAT does not have a built-in database for hybrid poplar or willow, so the database for poplar was modified with data provided from the USDA and other sources.

The model has limitations in modeling streamflow in the MRB. SWAT uses either the SCS curve number (CN) or Green-Ampt method to determine runoff. The Green-Ampt method requires subdaily precipitation data input, which is not available for the entire river basin, requiring that we disaggregate daily data to hourly. With the CN method, runoff is calculated as a function of hydrologic soil group, cover type, treatment, hydrologic condition, and antecedent runoff condition (Rawls et al. 1993). The curve number method becomes less accurate when runoff is less than 0.5 in (Rawls et al. 1993), reducing the validity of the technique for smaller runoff events. Conceptually, the SCS CN can be applied to mildly sloped watersheds without problem but, mildly sloped watersheds, like the MRB, tend to be wetter and overland flow plays a smaller role in total watershed response (Walker 2004). There are further limitations in applying the CN method for continuous streamflow simulations. As an agricultural watershed management tool, however, SWAT is suited for estimating monthly and annual water quantity and quality from watersheds under different crops.

### **HYDROLOGIC SIMULATION PROGRAM FORTRAN (HSPF)**

The HSPF model was a candidate model for this study because it has been successfully applied on the MRB under existing land-use conditions (Minnesota Pollution Control Agency 2003), and was used to estimate land-use change on a small watershed in the MRB (Miller 1999). It is a comprehensive, conceptual, continuous simulation model that can simulate the quantity and the quality of flow from small catchments to large river basins (Bicknell et al. 2000). It has a modular structure with three modules; the pervious land (PERLND), the impervious land (IMPLND), and the streams (RCHRES). A land segment is a subdivision of the simulated watershed. The segmentation size of land into homogenous segments could reduce the

lumping of the model that could be distributive. However, it is usually classified as a lumped model. The model needs a series of different climatic data, precipitation, and potential evapotranspiration are required and solar radiation, cloud, temperature, wind speed, and dew-point are optional but required when the snowmelt is simulated.

The hydrologic cycle is represented with a series of mathematical operations representing the hydrologic processes as flows and storages. In general, each flow is an outflow from storage, usually expressed as a function of the current storage amount and the physical characteristics of the subsystem. Although there is some physical basis for the model, many of the flows and storages are represented in a simplified or conceptual manner. Although this requires the use of calibrated parameters, it has the advantage of avoiding detailed physical dimensions and characteristics of the flow system in its three modules.

In pervious land segments HSPF simulates the movement of water along three paths: overland flow, interflow, and groundwater flow. Each of these three paths exhibits differences in time delay and in the interaction between the hydrologic processes occurring in the segment. (Donigina et al. 1995). A variety of storage zones are used to represent the storage processes that occur on the vegetation, land surface, and in the soil horizons.

A brief description of the key model parameters that represent vegetation characteristics in the following (EPA 2000) (see Table 1).

### **HSPF Vegetation Parameters**

- CEPSC: Amount of rainfall interception, in inches, which is retained by vegetation and is eventually evaporated.
- UZSN: Nominal upper zone soil moisture storage which is related to land surface characteristics, topography, vegetation, and LZSN. It differs between agricultural land to natural vegetative systems. It can change over the year and is related to overland flow; higher UZSN generates lower surface runoff.
- NSUR: Manning's n for overland flow plane. It expresses the surface roughness of the flow plane and depends on the surface conditions, vegetation, and topography. It affects overland flow and can be calibrated if surface runoff data are available.
- INTFW: Coefficient that determines the amount of water which infiltrates from surface detention storage and becomes interflow, as opposed to direct overland flow and upper zone storage.
- IRC: The interflow recession coefficient is the ratio of the current daily interflow discharge to the interflow discharge on the previous day. The IRC values are related to the INTFW values.
- LZETP: The index to lower zone evapotranspiration is similar to a crop ET coefficient. It affects evapotranspiration from the lower zone which represents the primary soil moisture storage and root zone in the soil profile. It is primarily a function of vegetative root depth.
- AGWETP: Fraction of model segment that is subject to direct evaporation from groundwater storage, e.g., wetlands or marsh areas, where the groundwater surface is at or near the land surface, or in areas with phreatophytic vegetation drawing directly from groundwater.

- BASETP: The index to ET by riparian vegetation from the baseflow.
- INFILT: Index to mean soil infiltration rate that effectively controls the overall separation of the available moisture from precipitation into surface and subsurface flow and storage components.
- LZSN: Lower zone nominal soil moisture storage is related to both precipitation patterns and soil characteristics. It affects ET and overland flow.

**Table 1.** Key hydrologic parameters for HSPF.

Name	Definition	Unit	Typical		Possible		Default	Function of	Comments
CEPSC	Interception storage capacity	mm	0.07	0.58	0.23	10.0	0	Vegetation type/density, land use, precipitation	Monthly values usually used
INFILT	Index of infiltration capacity	mm/hr	0.25	6.4	0.25	12.7	-	Soils, land use	CALIBRATION, divides surface and subsurface flow
NSUR	Manning's n (roughness) for overland flow	-	0.15	0.35	0.05	0.50	0.1	Surface conditions, residue, etc.	Monthly values often used for croplands
UZSN	Upper zone nominal soil moisture storage	mm	2.54	25.4	1.27	50.8	-	Surface soil conditions, land use	Accounts for near surface retention
IRC	Interflow recession parameter	none	0.5	0.7	0.3	0.85	-	Soils, topography, land use	Often start with a value of 0.7, and then adjust (calibrate)
LZSN	Lower Zone Nominal Soil Moisture Storage	cm	7.6	20.3	5.8	38.1	-	Soils, climate, land use	CALIBRATION
LZETP	Lower zone ET parameter	-	0.2	0.7	0.1	0.9	0	Vegetation /density, root depth	CALIBRATION
BASETP	Fraction of remaining ET from baseflow	-	0.0	0.05	0.0	0.20	0	Riparian vegetation	Direct ET from riparian vegetation

## HSPF Application

Application of the HSPF model requires that model parameters be calibrated under the various land use and vegetative conditions of interest. A key parameter is actual evapotranspiration (ET), which is a function of the potential ET (user input) and the amount of water available in the soil and on the land surface. As there is no plant-growth component in the model, the effects of vegetation growth, type, density, and rooting characteristics are lumped into parameters that control actual ET from different storages. CEPSC, UZSN, LZSN, and LZETP are critical parameters related to ET (Hydrocomp 1996) that must be adjusted to represent vegetative effects. Water balance calculations using precipitation and soil moisture determine ET for each cropping system. We will have both soil moisture and ET estimates from runoff plots under five crops at Waseca.

Overland flow (surface runoff) measured from runoff plots under different crops will help determine the parameter values for NSUR, INFILT, IRC, and INTFW (Hydrocomp 1996). For

determining the rest of the parameters, such as those associated with wetland and riparian vegetation, we will rely on the literature and then evaluate the responses from applying the watershed model.

## SUMMARY

Land use and vegetative cover play an important role in watershed runoff and streamflow discharge patterns over time, including peak flows. Because of earlier applications (and calibrations) of HSPF on the MRB, and the constraints of applying the SWAT model, we have selected the HSPF model to examine the hydrologic response to vegetative changes. Key processes that will need to be quantified and translated into model parameters, include interception, infiltration capacity, soil moisture storage—rooting depth relationships, ET–PET relationships, and surface roughness (Manning’s  $n$ ). We further need to simulate watershed conditions with and without drainage and wetlands. Work is underway to transform field data from runoff plots into model parameters, which will likely require some level of calibration. The uniqueness of overland flow, ET, and tile flow under different vegetative conditions can help us determine parameters that characterize different crops, including agroforestry, in the MRB.

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