Demonstration of GSSHA Hydrology and Sediment at Eau Galle Watershed Near Spring Valley, Wisconsin

by Charles W. Downer

PURPOSE: The purpose of this System-Wide Water Resources Program (SWWRP) technical note is to describe the application of the Gridded Surface Subsurface Hydrologic (GSSHA) model to the analysis of the watershed upstream of Spring Valley Reservoir located near Spring Valley, WI. GSSHA was applied at this watershed to demonstrate the capability of the model to simulate the hydrology and sediment transport in the Upper Mississippi River Valley region.

GSSHA MODEL: The GSSHA (Downer et al. 2005) model is the U.S. Army Corps of Engineers distributed hydrologic model. The computational domain within GSSHA is divided into uniform grid cells. Point calculations are made at each grid cell and the responses from grid cells are integrated to determine the system response to hydrometeorological inputs. In addition to hydrology, the model performs overland sediment detachment and transport, channel sediment transport, and overland and channel nutrient fate and transport. Each of these capabilities is presented in a brief discussion in the following paragraphs.

Hydrology. Critical to this study is the ability of the model to simulate the surface water response, the subsurface water response, and the interaction between the two systems, which determines the stream response. Other important model features are the ability to simulate extended periods of time (months to years) accounting for soil moisture between precipitation events and both accumulating and melting frozen precipitation. New features being demonstrated in this study are:

- nonorthogonal channels
- in-stream reservoirs
- hydraulic structures
- two-layer soil moisture accounting model coupled to the subsurface water model

Sediment Transport. GSSHA has the capability to simulate sediment detachment on the overland flow plane due to both rainfall impact and rill and gulley erosion. Once detached, sediments are transported according to the two-dimensional advection dispersion equation (Downer and Byrd 2007). Sediments in overland flow can settle in down gradient cells or be transported to the stream channel. Once in the channel, sediments are treated as either wash load and transported with the general transport equations, or as bed load and transported according to Yang's method (Yang 1996). The streambed is allowed to gain or lose in these simulations. New sediment transport features being demonstrated include:

- Particle detachment due to rainfall impact
- Rill and gulley erosion calculated with multiple methods
- Overland flow routing with advection-dispersion equation
- Sediment settling on overland flow plane due to settling velocity

Nutrient Transport. Nutrients, or other conservative or nonconservative constituents are transported in GSSHA according to the same general advection-dispersion equations used for sediment transport (Downer and Byrd 2007). Constituents may be specified as "first order reactants" and will be treated as constituents with uptake and decay controlled by first order reactions, with rates specified by the user. Alternatively for nutrients, nitrogen (N) and phosphorous (P) the rates of uptake from the soil, and the reaction rates can be provided by the Nutrient Simulation Model (NSM) (Johnson and Gerald 2006) which is coupled to the GSSHA model. The NSM model tracks numerous N and P species and calculates not only rates of decay but transformations between the different species.

DEMONSTRATION WATERSHED: The Eau Galle River watershed encompasses a 402 km^2 area in northwest Wisconsin (Figure 1).

In addition to this demonstration, the U.S. Army Engineer District, Saint Paul, is conducting a watershed study of the Eau Galle River using the GSSHA model. The purpose of this study is to analyze the effects of land use change on hydrologic response.

While the larger basin study is important, the lower portion of the basin (Figure 2) is relatively data poor. The data, particularly rainfall, are not sufficient for the testing of new model developments. GSSHA requires high quality rainfall data to accurately simulate both water and sediment runoff. The upper portion of the watershed, that portion above Spring

Figure 1. Location of Eau Galle River watershed.

Valley Dam, (Figure 3) has been the subject of intensive past studies, and compared to the lower portion of the watershed, is relatively data rich. This 103 km^2 subwatershed was selected to demonstrate the new features in the GSSHA model.
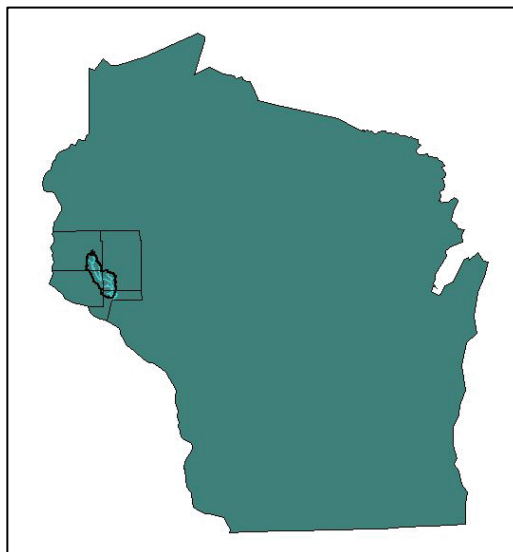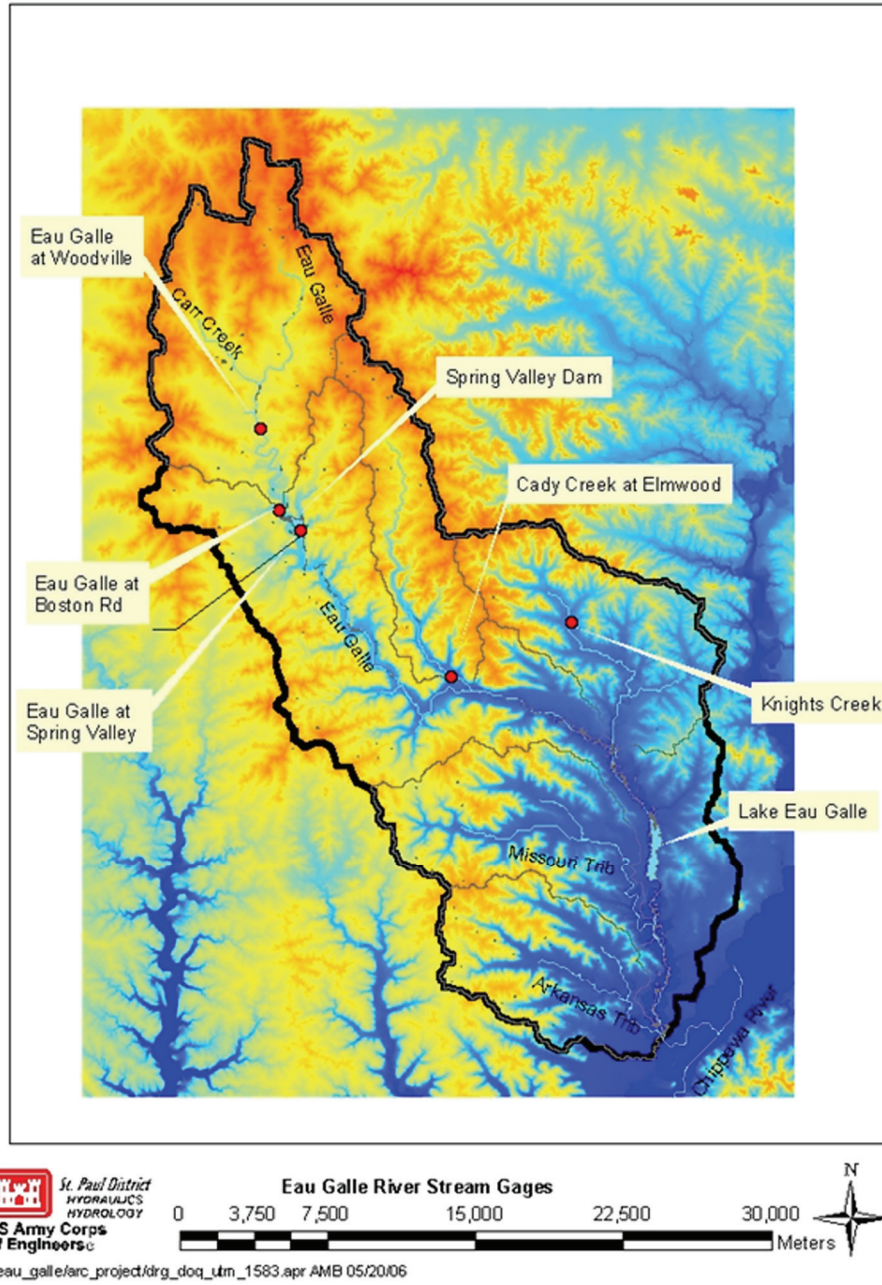
Figure 2. Eau Galle River watershed with sampling locations.
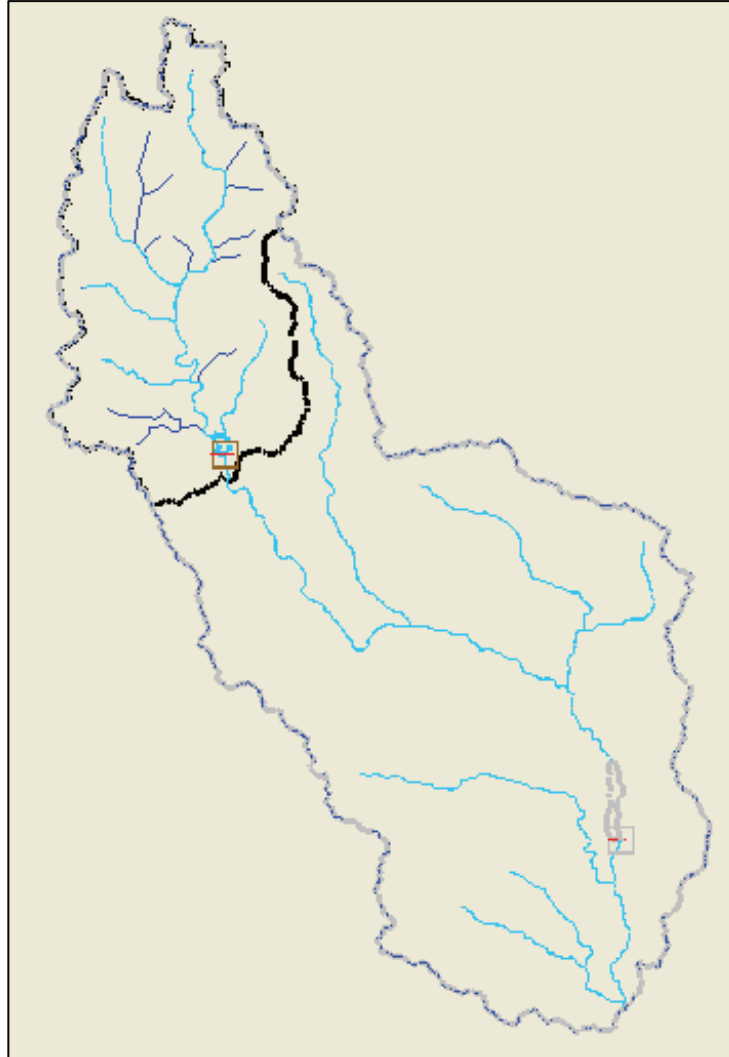
Figure 3. Spring Valley Dam watershed.

The following data are available for the period April 2002 through December 2003:

- 15-min. gauge data from seven streamflow gauges for the period 2002 -2003. U.S. Geological Survey (USGS) gauging stations are located above and immediately below the Spring Valley Dam. Six gauges above the dam were maintained by the U.S. Army Engineer Research and Development Center's Environmental Laboratory, including one overlapping site with the upstream USGS gauge (Figure 4).
- Nutrient, sediment, and basic water quality parameters at multiple locations for selected storms during the period 2002-2003.
- 15-min. precipitation from eight gauges in and around the basin
- Hourly stage and discharge at Spring Valley Dam

In addition to the available data, the Spring Valley Dam watershed has these important features:

- Reservoir with controlled discharge
- Mixed hydrology basin with contributions from surface and subsurface

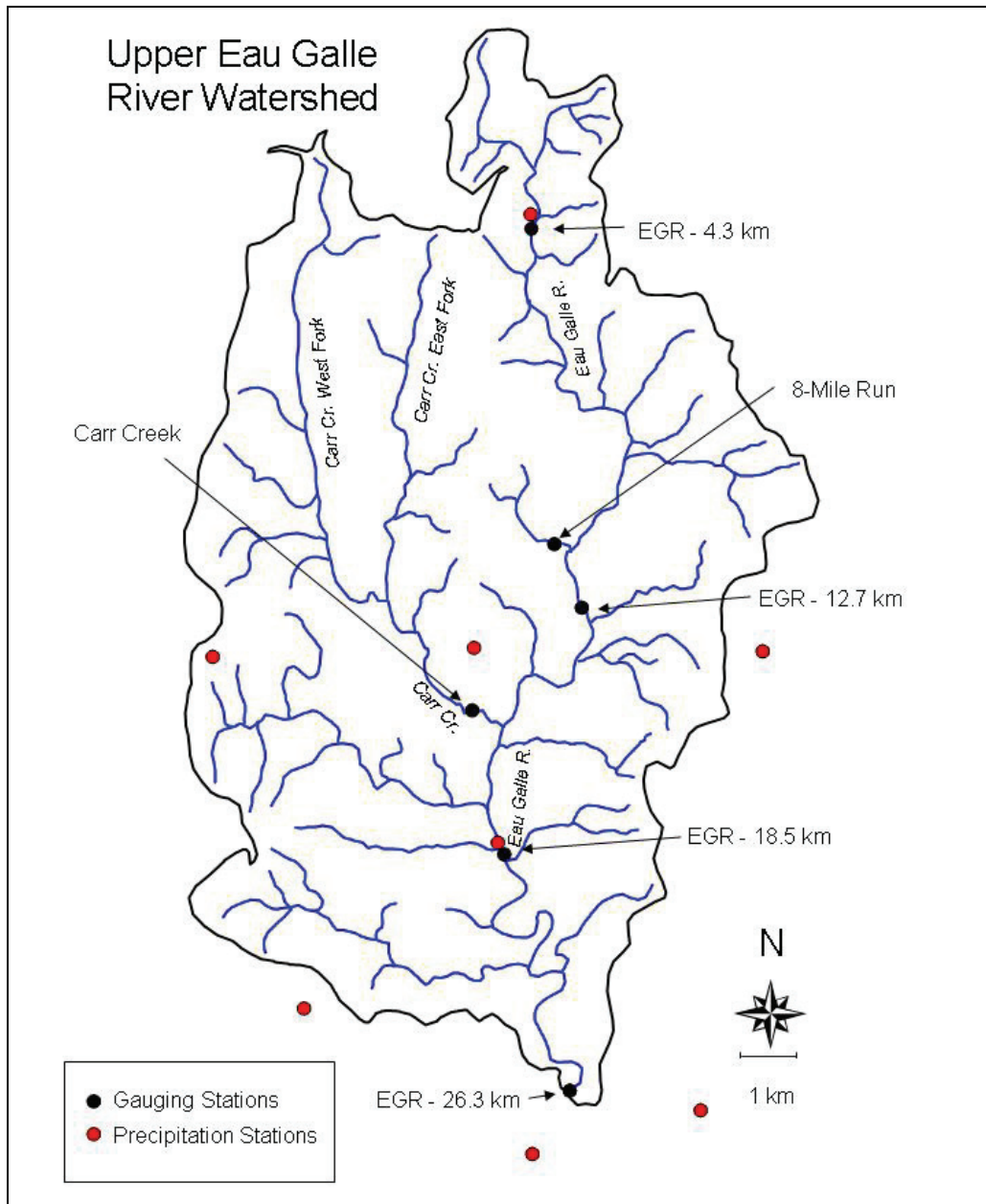- Agricultural basin with diffuse nutrient sources
- Dendritic stream network

Figure 4. Upper Eau Galle River watershed measurement sites.

MODEL DEVELOPMENT: To simulate this basin, a coupled surface water groundwater model was developed from available data. Surface information was taken from the original Eau Galle River study and supplemented with subsurface information. As with the original study, a 100-m grid resolution was selected. This resolution allows for adequate description of important landscape features, primarily fields, maintains surface slopes, and allows for reasonable

computation times. The 100-m resolution results in 17,500 active cells for the region shown in Figure 5. All first, second, and third order streams were included, as shown in Figure 5.

The stream network consists of 54 stream reaches with 854 nodes, each approximately 90 m in length. The new stream routing routines allow the streams to be discretized without regard to the overland flow cell size, allowing the model to better represent the actual stream network. Trapezoidal cross sections were developed from site surveys. The field data were also used to adjust the stream bottom elevations, even though no actual stream bottom elevations were available. Top of bank elevations were used along with the surveyed channel cross sections to provide an estimation of stream bottom from these two data sources. The amount that the streams are incised into the landscape is important for determining surface groundwater interaction with the stream. All streams in the network include groundwater interaction parameters along with uniform parameters for channel roughness, bottom layer thickness, and bottom layer hydraulic conductivity.
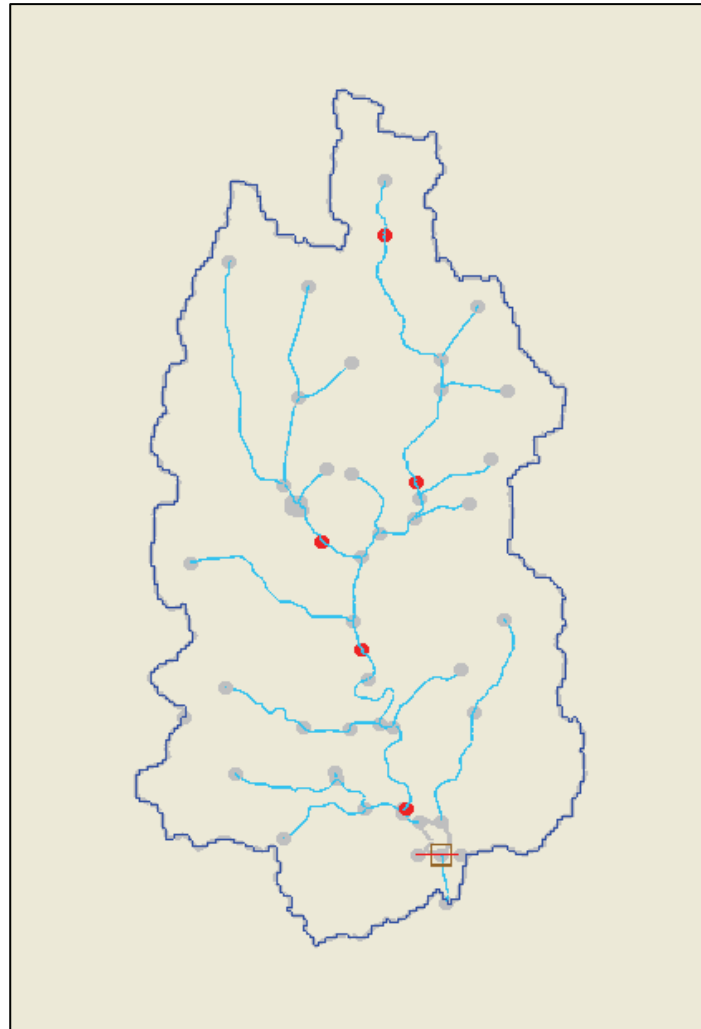

Figure 5. Model domain showing channel features.

The Spring Valley Reservoir is simulated as part of the stream network. The elevation-storage information is provided by the overland flow grid. The reservoir outflow is computed according to the stage-discharge curve in the Water Control Manual (USACE 2003) for the lake (Figure 6).
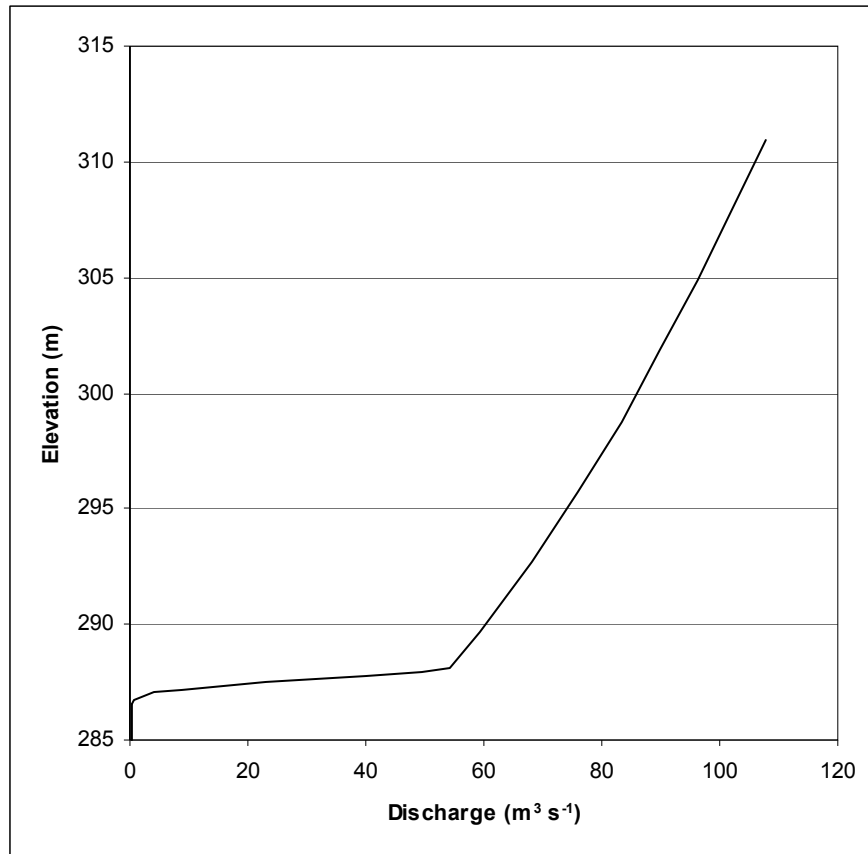

Figure 6. Spring Valley Dam discharge rating curve.

USGS 30-m National Elevation Dataset (NED) digital elevation maps were used to develop the land surface elevations for the grid. The Natural Resources Conservation Service (NRCS) Soil Survey Geographic Database (SSURGO) soils data were used to describe the soils. The 1992 digital land use data were provided by the Saint Paul District.

The subsurface was conceptualized from *wisc*LITH (Wisconsin Geological and Natural History Survey 2004) data with help from personnel at the Wisconsin Geological and Natural History Survey. According to these sources there are several confining dolomite layers within the watershed that have been eroded over time to various degrees in the watershed, resulting in a stair-step confining layer. The confining layers are overlaid by unconsolidated materials, sand and gravel, which range from 0 to 30 m in depth. Below the confining layer is a sandstone aquifer. Although sources at the survey indicated that the water table should not be found in the unconsolidated materials, there is base flow in the streams. The source of the base flow could be flow from the unconsolidated materials or from fractured bedrock. In either case the materials above the confining layer were treated the same.

The *wisc*LITH data consist of lithographic and stratigraphic descriptions from thousands of samples from wells and boreholes. The *wisc*LITH data were searched for boreholes through or to these known confining layers. The depth to the confining layers was used in conjunction with the Digital Elevation Model (DEM) data to assign a bedrock depth to individual data points. The Watershed Modeling System (WMS) was then used to interpolate a bedrock elevation map from the 1,299 points of data. The bedrock elevation map was developed for the larger Eau Galle River study region. As the elevation data in *wisc*LITH could be off by 3 m, the minimum depth to the shallow confining layer was set to 3 m. In addition to including the uncertainty in the data source, setting a minimum aquifer depth ensures that the conceptualized groundwater model is feasible to solve computationally. The final bedrock elevation map has a groundwater media thickness ranging from 3 to 90 m. As seen in Figure 7, the subsurface media is generally deeper in the uplands and shallowest near the streams. According to the USGS, hydraulic conductivities in the shallow groundwater media are on the order of 10 cm/hr.
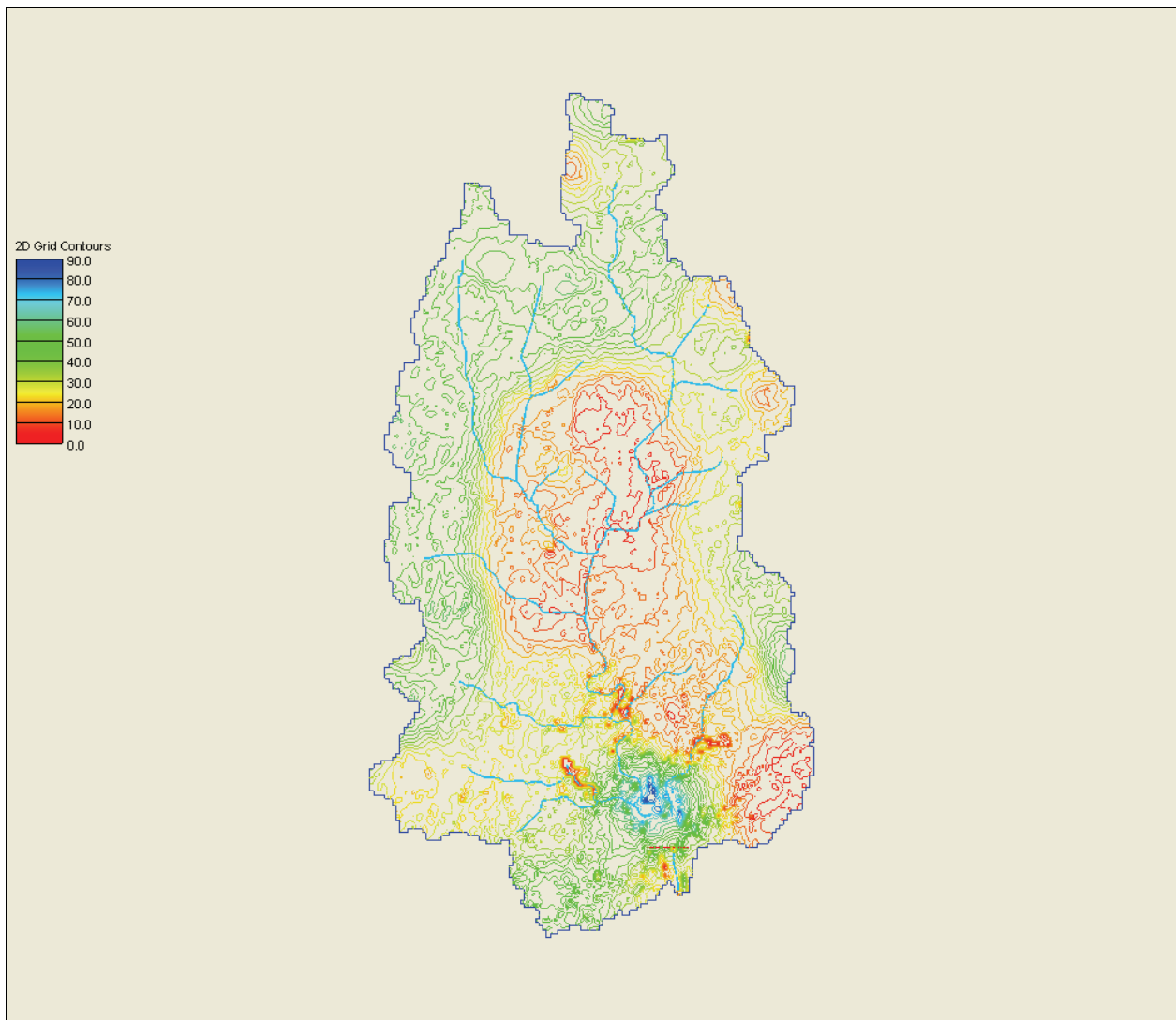

Figure 7. Depth to bedrock (m).

A ridge around the watershed isolates the shallow-water table from the shallow aquifer system, which is approximately 100 m below the land surface and does not interact with the surface layer above the confining dolomite layers, the zone that affects the streams in the study. A no-flow boundary condition is imposed around the perimeter of the watershed. While it is possible that shallow flow could pass through the southern boundary, the no-flow conditions force all groundwater to leave the watershed via the stream network. All stream segments are specified as river flux boundaries, such that they interact with the saturated groundwater in the surface layer.

HYDROLOGIC PARMETER ASSIGNMENT AND CALIBRATION: Distributed parameters for interception, overland flow, infiltration, evapotranspiration and sediment detachment were assigned according to land use and soil type. Categories in the soil type and land use maps were condensed, and then combined, to develop GSSHA index maps to assign parameters to the model. Six land uses and six soil textural classifications were combined to produce 10 soil type/land use (STLU) categories. The land use and STLU type maps are shown in Figures 8 and 9, respectively. The land uses in Figure 8 are:

- 2: residential
- 4: commercial
- 6: forest
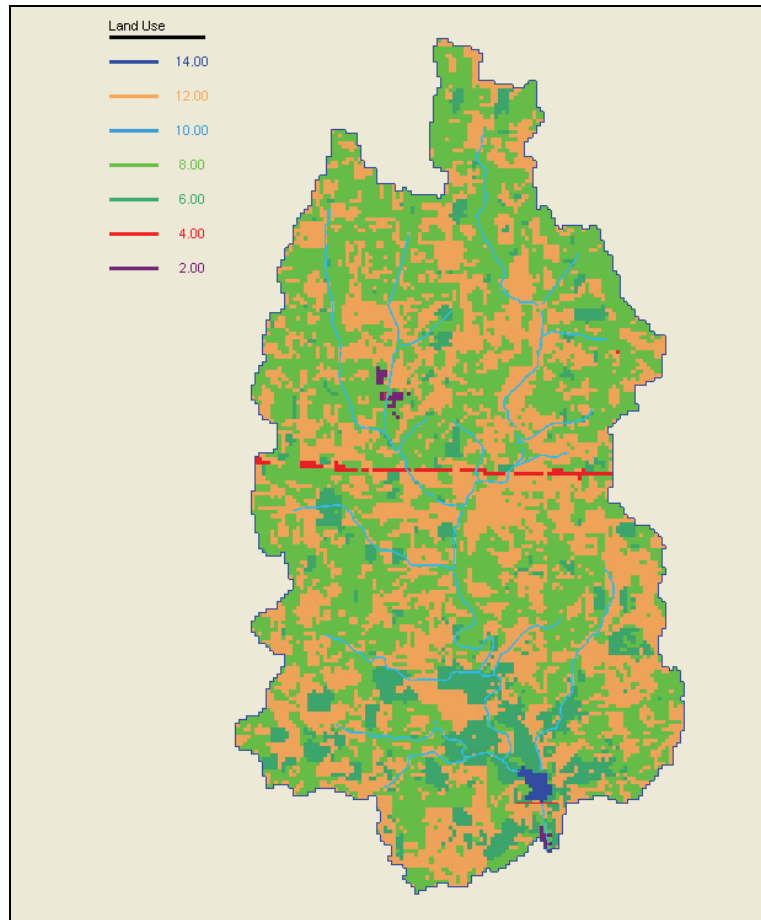- 8: grass
- 10: wetland
- 12 : row crop
- 14: open water

Figure 8. Land use.

The predominate land uses in the basin are pasture (8, light green) and row crops (12, beige). There is a moderate amount of forest (6, dark green), with limited residential and commercial use.

STLU classes in Figure 9 are:

- 101: coarse
- 102: residential coarse
- 103: sandy loam
- 104: loam
- 105: silty loam
- 106: residential silty loam
- 107: row crop silty loam
- 108: rocky
- 109: commercial
- 110: water

The predominant soil type is silty loam. The predominant STLU types are undifferentiated silt loam, 105; residential silt loam, 106; and crop silt loam, 107.

Uniform parameters were assigned for channel roughness, channel bed sediment thickness, channel bed hydraulic conductivity, groundwater media porosity, and groundwater media lateral hydraulic conductivity. Values of vegetative storage capacity (C_l), overland roughness (n_{ov}), overland retention depth (d_{ret}), saturated hydraulic conductivity (K_{sat}), channel roughness (n), channel bed hydraulic

Figure 9. STLU classes.

conductivity (K_r), and saturated groundwater lateral hydraulic conductivity (K_{gw}) were tuned such that model output more closely matched observed flows.

The model was primarily calibrated to observed flows at the USGS gauge (EG 18.5 in Figure 4) because this site was believed to provide the most reliable data for model calibration. Flows from the other sites are considered less reliable because the rating curves for the sites were developed from dating ranging over only a portion of the observed flows, such that the accuracy of the higher flows is unknown. Flows from these sites were used in a more qualitative manner, with emphasis placed on matching the pattern of flows observed at the sites. A combination of manual and automated calibration was performed. Event peaks and total discharge volumes were used as the calibration criteria.

Originally the model was calibrated for the June 2002 period. For this calibration, the model simulation began May 1, and continued through June 30. The month of May was used as a startup period for the groundwater simulations. Prior to beginning calibration, the groundwater
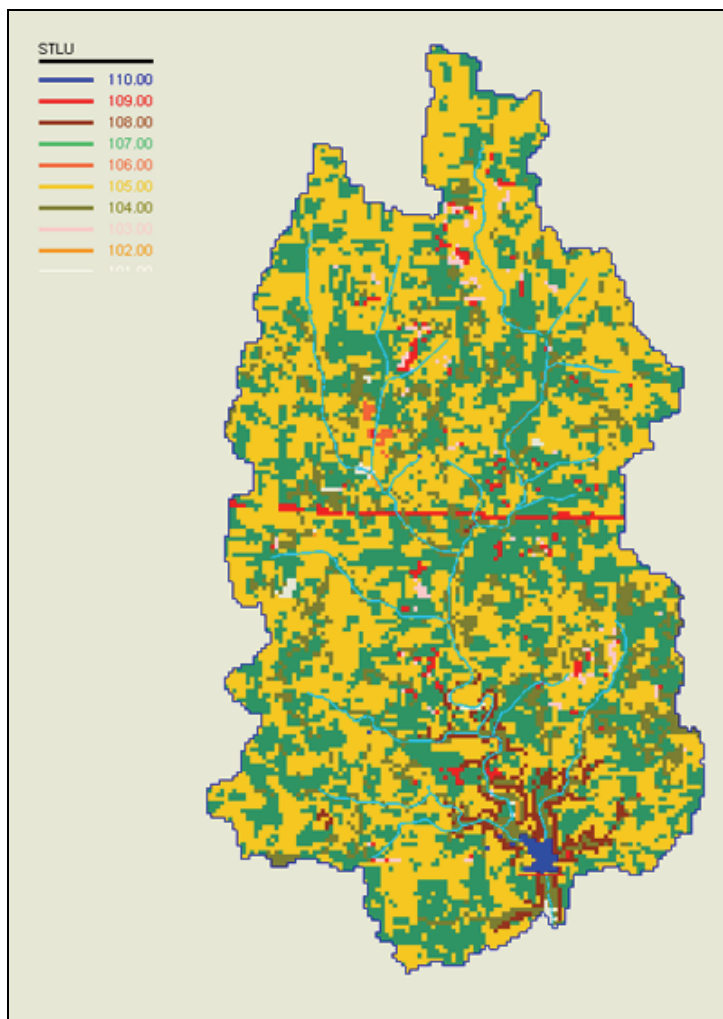
model was initialized by imposing an initial water surface and running the model for an extended period. The initial water surface was interpolated from observed water table measurements from six locations in and around the Eau Galle watershed for the period 2002 and 2003. These data were obtained from the Wisconsin Department of Natural Resources (WDNR) and private entities. The model was then run for an extended period of time until the April 2002 water table measurements observed at wastewater seepage cells near Woodville, WI were reproduced in the model. This water table was used as the starting condition.

Results of the calibration are shown in Figure 10. As seen in pane 1 of Figure 10, the model was able to match the observed flows. The mean absolute error (MAE) of the larger two peaks is 3 percent of the observed. The error in total discharge is 1.5 percent of observed. The hydrograph shapes and base flow are accurately reproduced.
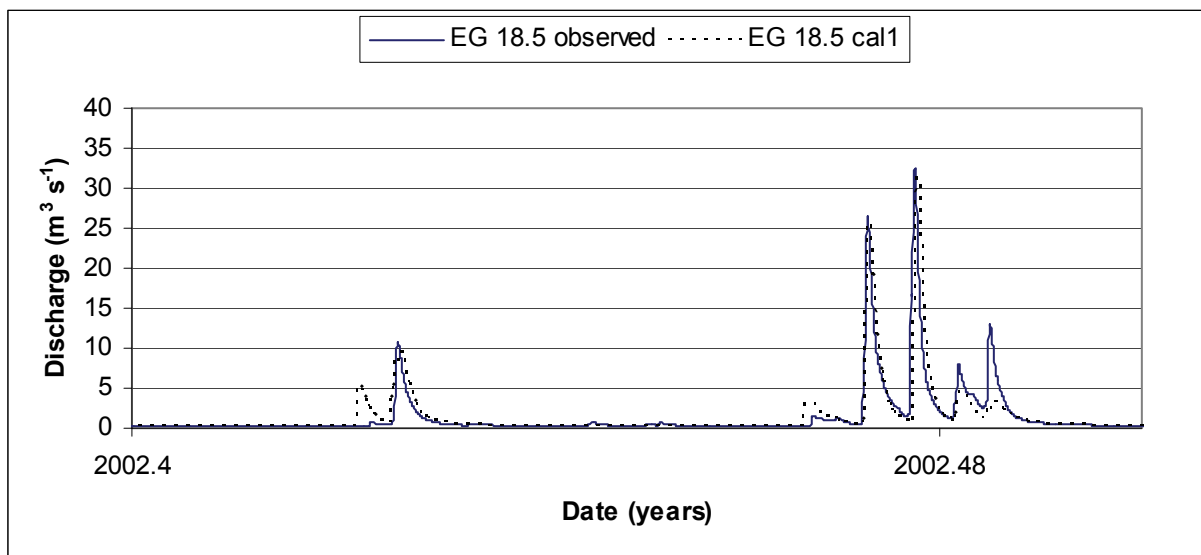

Figure 10. Initial calibration results, May 15-June 30, 2002.

When attempting to validate the model using a period of time extending through October 2002, the calibrated model performed poorly. The model discharge at the gauge station greatly exceeded the observed discharge for this time period. The model was recalibrated to the longer period, June through October 2002. The recalibrated model demonstrates acceptable skill in predicting streamflow at the gauge station during the period except for a single large event that occurs on August 20, 2002, shown in Figure 11. According to the precipitation gauges, the event produced an average of 83 mm of rainfall over the basin, yet surface flow gauges indicate little runoff. The model predicts approximately 25 percent of the rainfall contributing to streamflow, greatly exceeding the observed flow. Other similar size events occurring during approximately the same dry conditions produce much greater discharge, on the order of 25 percent of rainfall, and are more accurately simulated by the model. To date, investigations into the loss of water occurring on the ground, or in the stream, are not clear. More field investigations are required to determine the losses that result in so little observed runoff. In previous studies, such conflicting results have identified poor data sets. However, in this case the cause remains unclear. Also, the

cause for the inability to simulate the later summer events with the calibrated early summer parameter set also remains unclear.
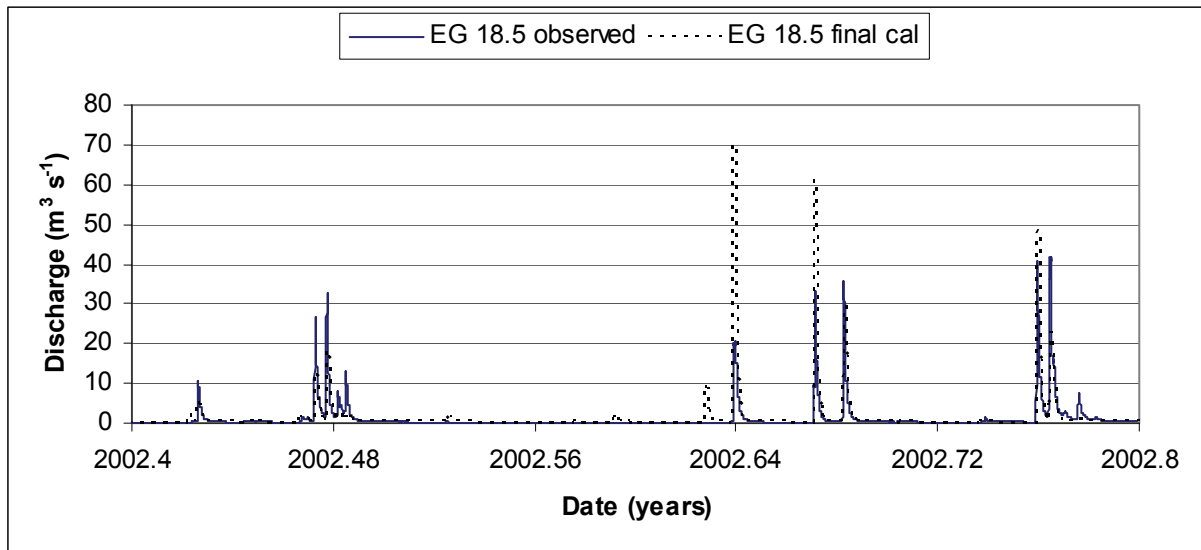

Figure 11. Final calibration results, May 15-October 19, 2002.

Parameter values for both calibration efforts are presented in Table 1. In addition to the distributed parameters, the following uniform values were applied:

- n : 0.037
- K_r: 4.43 cm hr^{-1}
- Groundwater porosity: 0.40
- K_{gw}: 11.19 cm hr^{-1}
- Soil moisture depth: 25 cm

Where: C_I is the interception capacity (cm), n_{ov} is the overland roughness coefficient, d_{ret} is the overland retention depth (mm), K_{sat} is the soil saturated hydraulic conductivity (cm hr^{-1}).

Excluding the single event poorly simulated, the mean absolute error (MAE) of peak flow was 42 percent of observed, and the total discharge was within 7 percent of the observed.

Table 1
Calibrated Hydrologic Parameter Values

Land Use	Soil Type	C_l Cal1	n_{ov} Cal1	d_{ret} Cal1	K_{sat} Cal1	C_i Final	n_{ov} Final	d_{ret} Final	K_{sat} Final
forest		1.000	0.165	1.000		1.000	0.165	0.000	
grass		0.000	0.120	1.000		0.042	0.235	0.000	
wetland		0.508	0.500	10.000		0.508	0.500	10.000	
crop		1.143	0.120	1.000		1.143	0.240	0.000	
residential		0.000	0.120	1.000		0.042	0.235	0.000	
commercial		0.000	0.013	0.000		0.000	0.013	0.000	
	coarse				12.000				12.000
residential	coarse				6.000				6.000
	sandy loam				1.09				1.09
	loam				0.450				0.650
	silty loam				0.131				0.157
residential	silty loam				0.130				0.174
crop	silty loam				0.036				0.048
	rocky				0.200				0.200
	commercial				0.010				0.010

MASS BALANCE AND WATER BUDGET: Mass balance is tracked for five domains. For each of the domains the percentage mass balance error is significantly less than one percent. The five domains and the mass balances for each are:

Overall: -0.007862%
Surface inputs: -0.033574%
Soil profile: 0.000000%
Perennial lakes: 225.54 m^3
Groundwater: 0.01%

GSSHA also provides information on the fate of water in the system (Table 2). As seen in the table, for the summer period at least most precipitated water is infiltrated and then evaporated. Overall streamflow is primarily from surface runoff. While the exchange back and forth is large, around 200 x 10^6 m^3, the net difference is small compared to the lateral inflow into the channels.

**Table 2
Spring Valley Dam Watershed Water Budget, May 15 –
October 19, 2002**

Input	Volume 10^6 m^3	Percent of Precipitation
Precipitation	1256	
Interception	79	6
Infiltration	1026	82
Evaporation	859	68
Groundwater recharge	234	19
Discharge	250	20
Lateral flow into channels	200	16
Groundwater flow into channels	45	4

RESERVOIR SIMULATION: The reservoir was simulated for the final calibration period using the updated discharge rating curve provided by the Saint Paul District. Since the discharge rating curve is for the morning glory outlet structure only, discharge was added to account for the hypolimnic flow structure. Typically the hypolimnic structure gate is set to 0.12 m, resulting in discharges of approximately 0.3 m^3 s^{-1}, depending on lake level (USACE 2003).

Discharges from the reservoir are shown in Figure 12. Outlet discharges are computed from stages (Figure 13). As shown in the figures, the model is capable of reasonably reproducing the reservoir discharges and water level. The figures show more error when the stages are high and the flows are larger. A closer look at the computed discharge provided shows that the computed discharges do not follow the discharge rating curve in the Water Control Manual (Figure 14). The differences are greatest when the stages are higher. In general, the discharge rating curve produces higher flows than observed for given stages, resulting in the model producing flows higher than observed, and stages lower than observed (Figures 12 and 13, respectively). It is thought that construction at the outlet works during this period results in the miscalculation of flows. In addition, District personnel also report flow from the morning glory outlet is often obstructed by debris during lower flow conditions, leading to reduced flows. Still, the model is able to reproduce the total flow within 3 percent of the observed flow from the reservoir, 2.09 x 10^7 m^3.
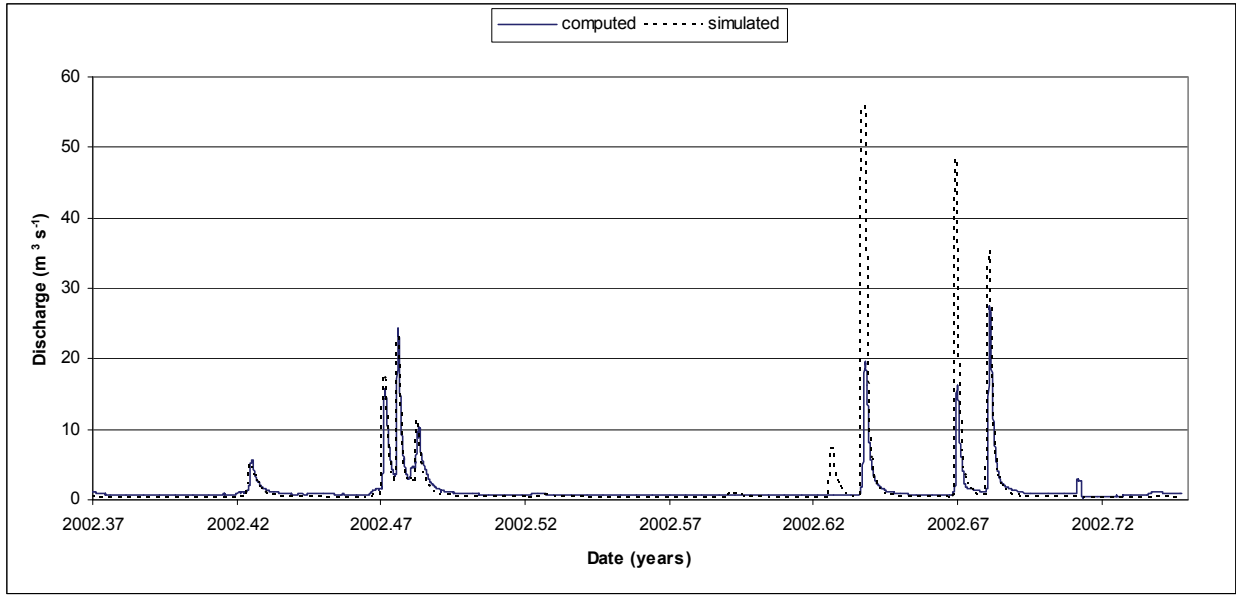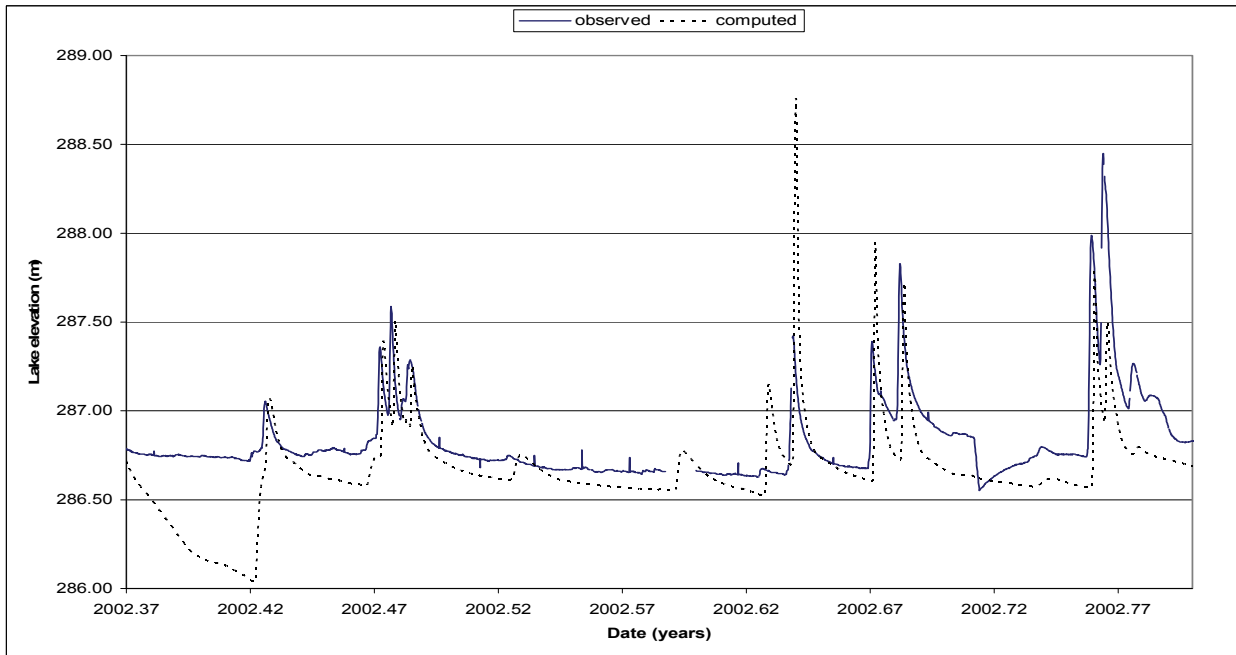
Figure 12. Reservoir discharge.
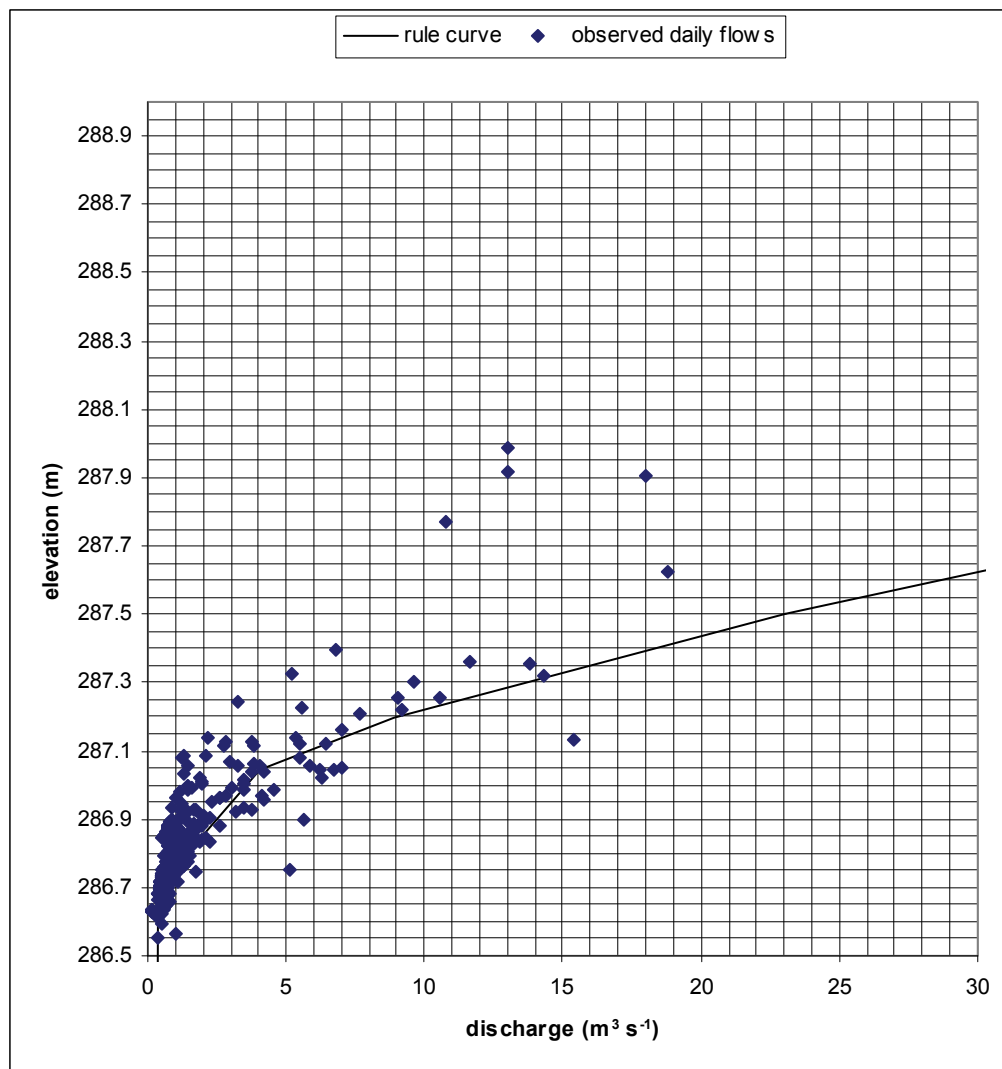

Figure 13. Reservoir stage.

Figure 14. Rating curve plotted with observed stage-computed discharge.

SEDIMENT SIMULATION: Three sediment size fractions were simulated, sand, silt, and clay. Sediments in the model were simulated using the Kilinc-Richardson formulation for gulley and rill erosion (Kilinc and Richardson 1973). In the current version of GSSHA, the three factors discussed in the user's manual are combined into the single erodibility factor. The erodibility factor, E, was assigned based on the STLU. Original values were taken from the GSSHA user's manual (Downer and Ogden 2006). These factors were calibrated to two observed events that occurred in June 2002 using the hydrologic parameters from calibration 1. Observed values of total suspended solids (TSS) and flow were combined according to USGS standards to produce sediment discharge ($m^3\ s^{-1}$) and compared to the model stream values of wash load, which is composed of clay and silt size fractions. The sand is expected and assumed to move as bed load and not be in TSS measurements. The final calibrated erodibility factors for the nine STLUs are shown in Table 3.

Table 3
Calibrated Kilinc Richardson Erodibility Factors

STLU #	Description	Erodibility (E)
101	coarse	0.0005
102	residential coarse	0.0005
103	sandy loam	0.00067
104	loam	0.0085
105	silty loam	0.0011
106	residential silty loam	0.0011
107	row crop silty loam	0.0086
108	rocky	0.0011
109	commercial	0.0005
110	water	0.000001

The calibration results are shown in Figure 15. The MAE for the total sediment discharge (m^3) for the two events was 12 and 4 percent of the observed, respectively.
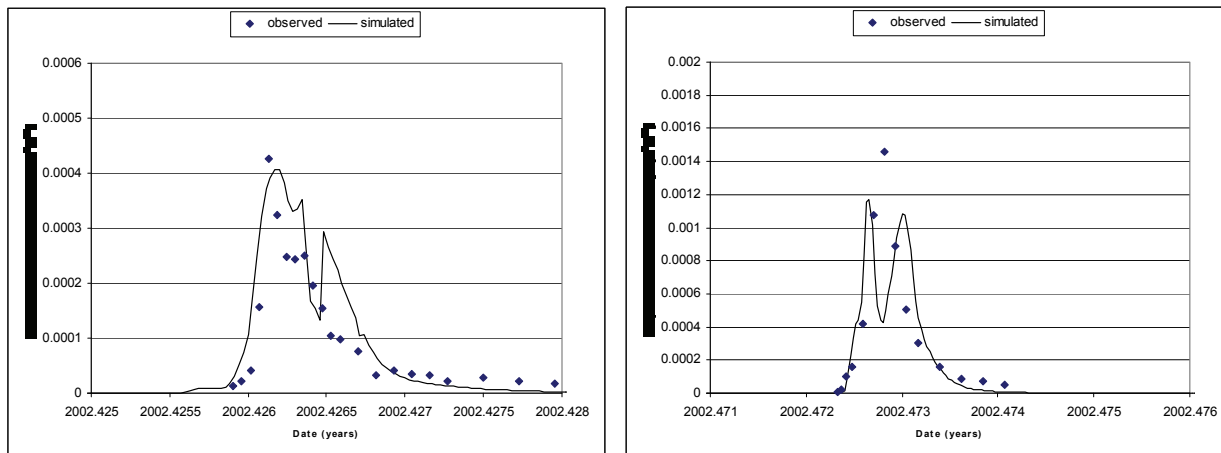

Figure 15. Sediment calibration events.

The erodibility factors were verified using the remaining 2002 data sets. Two significant events were recorded for this period. The first event was the one for which the model poorly predicted flow, and the sediment discharge prediction was also poor, with the MAE of 142 percent of measured, pane 1 in Figure 16. For the second event, the hydrologic prediction was good, and the model was able to reproduce the total event sediment discharge within 12 percent of measured, similar to the calibration results, pane 2 in Figure 16. In Figure 16, discharge is shown on the right y-axis and sediment discharge is shown on the left y-axis.

Small events, <1 m^3 total sediment discharge, recorded during the calibration/verification time frame were not well simulated. The GSSHA model overestimates sediment discharge for small events even when the hydrologic predictions are good. Such events usually represent only a small portion of the total sediment load and are not considered significant. Since observed

sediment data were available only for selected events, no comparisons to the total sediment load for the entire period can be made.

In general, the sediment calibration and verification results are good. For events where the discharge is well simulated, the errors in total sediment discharge are on the order of only 10 percent. Sediment discharge for the poorly simulated event is in proportion to the size of the simulated discharge. The ability to simulate sediment discharge accurately lends confidence that not only can the model simulate the hydrology, it does so for the correct reasons, as correctly simulating sediment discharge is highly correlated to simulating the overland flow depths and velocities correctly.
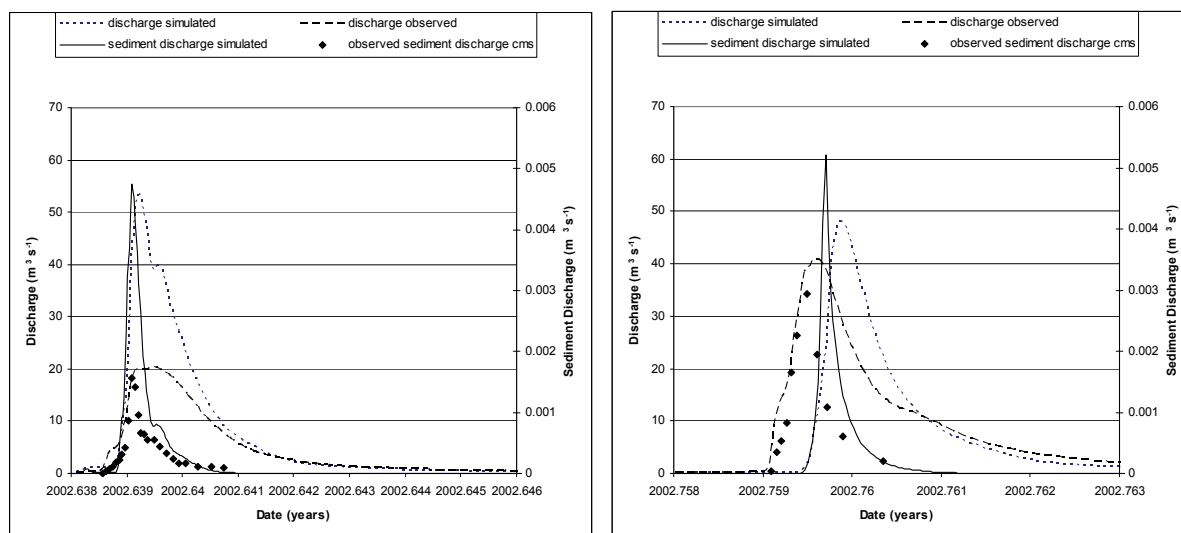

Figure 16. Sediment verification events.

SUMMARY: The GSSHA model was applied to the watershed upstream of the Spring Valley Dam located on the Eau Galle River in northeast Wisconsin. Land use in the watershed is primarily agriculture. In addition to the concern about agricultural effects on water quality in the lake and river, there are concerns about the effects of land use change on hydrologic and water quality conditions in the larger Eau Galle River system. The GSSHA model was able to adequately simulate hydrology as seen by the calibration during the period June through October 2002. Although the hydrologic model calibration was acceptable in terms of overall performance, the model overestimated some of the larger late summer events. Sediment loads were simulated with considerable skill for periods when the hydrology was simulated well and poorly for periods where the hydrologic model performed poorly. Based on these results, it has been demonstrated that the GSSHA model has the capability to simulate hydrology, hydraulics, and sediment transport in the Eau Galle watershed. The ability to simulate the sediments with great accuracy indicates that the model accurately reproduces the runoff generating processes, and not just the correct amount of runoff. Given these results, it is anticipated that GSSHA will also be able to simulate the fate and transport of nutrients as well. The resulting model should prove to be an effective tool to assess relative difference in hydrology and transport due to changing land uses and implementation of best management practices in the watershed. Demonstration of the model for simulating nutrients will be presented in a companion technical note.

ADDITIONAL INFORMATION: This technical note was prepared by Dr. Charles W. Downer, research hydraulic engineer, Coastal and Hydraulics Laboratory, U.S. Army Engineer Research and Development Center. The study was conducted as an activity of the GSSHA Hydrology and Sediment work units of the System-Wide Water Resources Program (SWWRP). For information on SWWRP, please consult https://swwrp.usace.army.mil/ or contact the Program Manager, Dr. Steven L. Ashby at Steven.L.Ashby@usace.army.mil. Coordination between participants of this demonstration and the Saint Paul District study team, primarily Ann Banitt, was accomplished in order to facilitate data exchanges and model setup. Paul Juckem, of the Wisconsin Geological and Natural History Survey, provided extensive help in conceptualizing the subsurface media. This technical note should be cited as follows:

Downer, C.W. 2008. *Demonstration of GSSHA hydrology and sediment transport at the Eau Galle Watershed near Spring Valley, WI.* ERDC TN-SWWRP-08-2. Vicksburg, MS: U.S. Army Engineer Research and Development Center. https://swwrp.usace.army.mil/

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