A Distributed Watershed Hydrologic, Sediment, Nutrient Transport and Fate Model

Zhonglong Zhang
BTS, U.S. Army Engineer Research and Development Center, USA

Billy E. Johnson
U.S. Army Engineer Research and Development Center, USA

Charles W. Downer
U.S. Army Engineer Research and Development Center, USA

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Zhonglong Zhang[a], Billy E. Johnson[b] and Charles W. Downer[b]

a. BTS, U.S. Army Engineer Research and Development Center 3909 Halls Ferry Road, Vicksburg, MS 39180 (Email: zhonglong.zhang@usace.army.mil)
b. U.S. Army Engineer Research and Development Center, 3909 Halls Ferry Road, Vicksburg, MS 39180 (Email: billy.e.johnson@usace.army.mil, charles.w.downer@usace.army.mil)

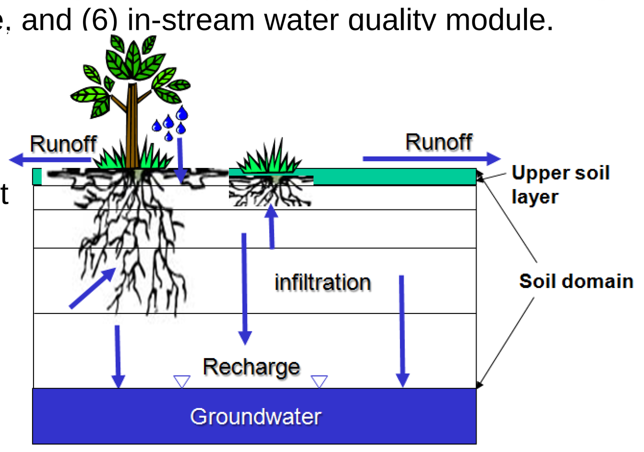
1 Overview

A distributed watershed hydrologic, sediment, nutrient transport and fate model - GSSHA was developed at U.S. Army Engineer Research and Development Center (ERDC). GSSHA was intended to be a complete physics based watershed analysis model and includes important processes related to the generation of runoff, stream routing, overland and stream sediment processes, and constituent transport.
GSSHA is a physically-based, distributed-parameter, structured grid, hydrologic model that simulates the hydrologic response of a watershed subject to given hydrometeorological inputs. The watershed is divided into cells that comprise a uniform finite difference grid. Processes that occur before, during, and after a rainfall event are calculated for each grid cell and then the responses from individual grid cells are integrated to produce the watershed response. The model can be used for complete assessment of sediment fate, from erosion on the uplands to deposition in the water body. The fate of associated contaminants (nutrients, toxic chemicals) can also be tracked through the coupled system. GSSHA can be used in a variety of environments, from arid desert regions in the west to humid forest on the eastern shore. The distributed and physically based nature of the model makes it applicable for the analysis of future conditions, such as land use changes, and management scenarios, watershed restoration, BMPs, etc., for flood control, sediment transport, and pollutant control.

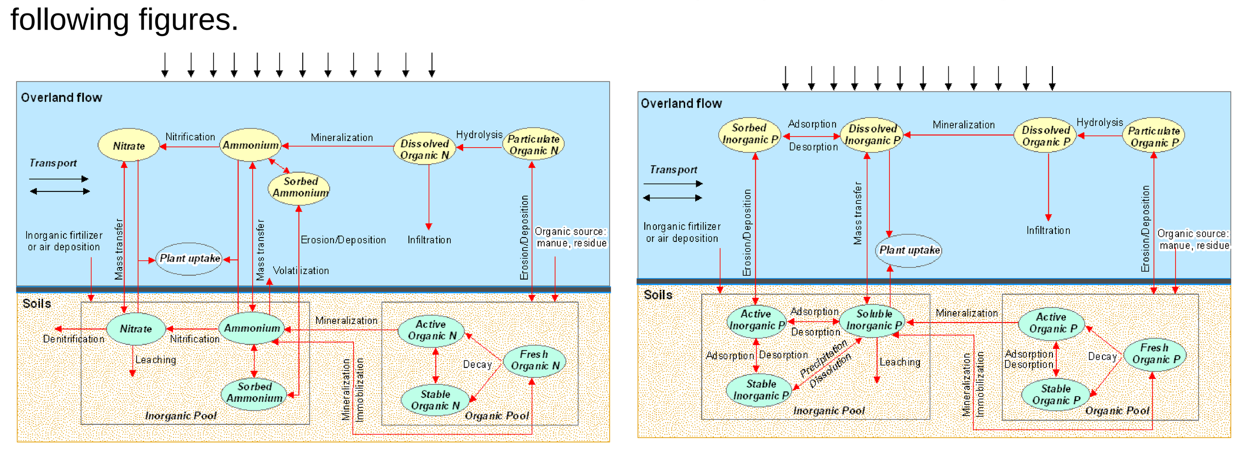
4 Nutrient Simulation Module (NSM)

There are two components to simulate the transport and fate of nutrients (N, P). The first component is for transport of reactive or nonreactive materials throughout the watershed, both insoluble and dissolved. The second component is a flexible biogeochemistry module that simulates the water quality state variables and transformation processes. Nutrient Simulation Module (NSM) was developed as a generalized water quality component for modeling chemical, biological, ecological processes and interactions between nutrient state variables in watershed and riverine systems. Water quality state variables included in NSM can either be transported by advection-dispersion processes or storage routing depending on the water engines. Conceptually three hydrologic domains and associated nitrogen pathways in the watershed were modeled by NSM: (1) subsurface soils, (2) overland flow, and (3) channel flow. NSM has separate modules to address individual elements/nutrients. Currently NSM includes the following individual modules: (1) subsurface soil nitrogen module, (2) subsurface soil phosphorus module, (3) soil plant dynamic module, (4) overland flow nitrogen module, (5) overland flow phosphorus module, and (6) in-stream water quality module.

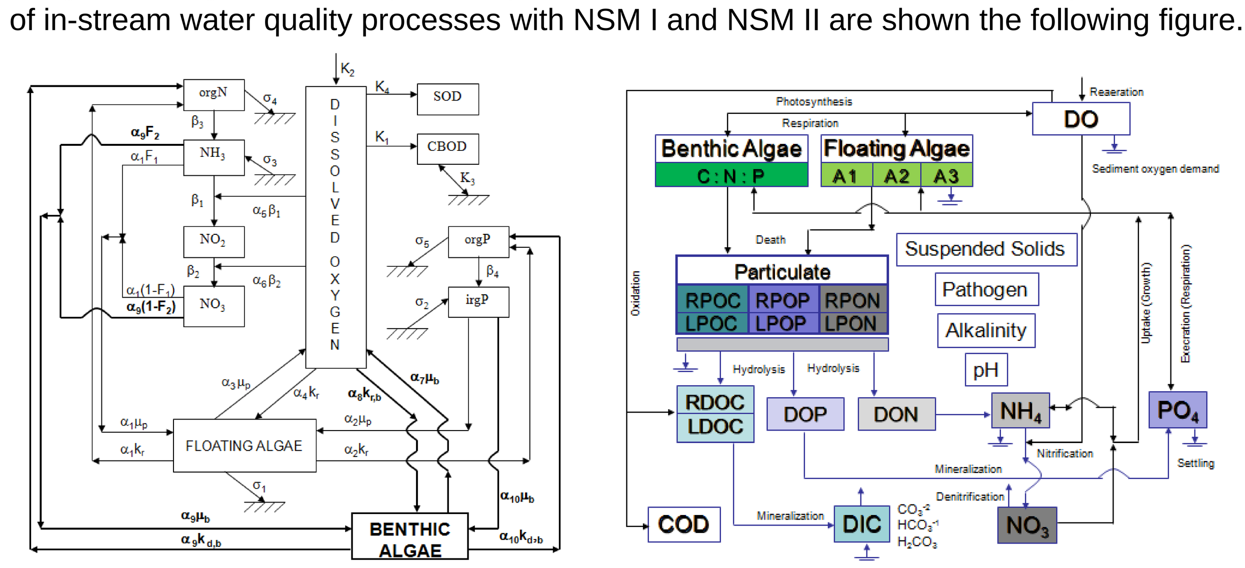
Soil nitrogen cycling is simulated in NSM for the five pools for each of the soil layers. Soil phosphorus cycling is simulated by NSM for the six pool state variables. In NSM, dominant N and P transformation processes are simulated for PON, DON, NH4, NO3, POP, DOP, PIP, DIP, DO, and Chla. The riverine biogeochemical simulation of nutrients is included in NSM at different levels .The mass balance equations for each state variable are not included here.



Schematic representations of the nitrogen and phosphorus transport and transformation processes involved in the watershed nitrogen and phosphorus cycle are given in the following figures.

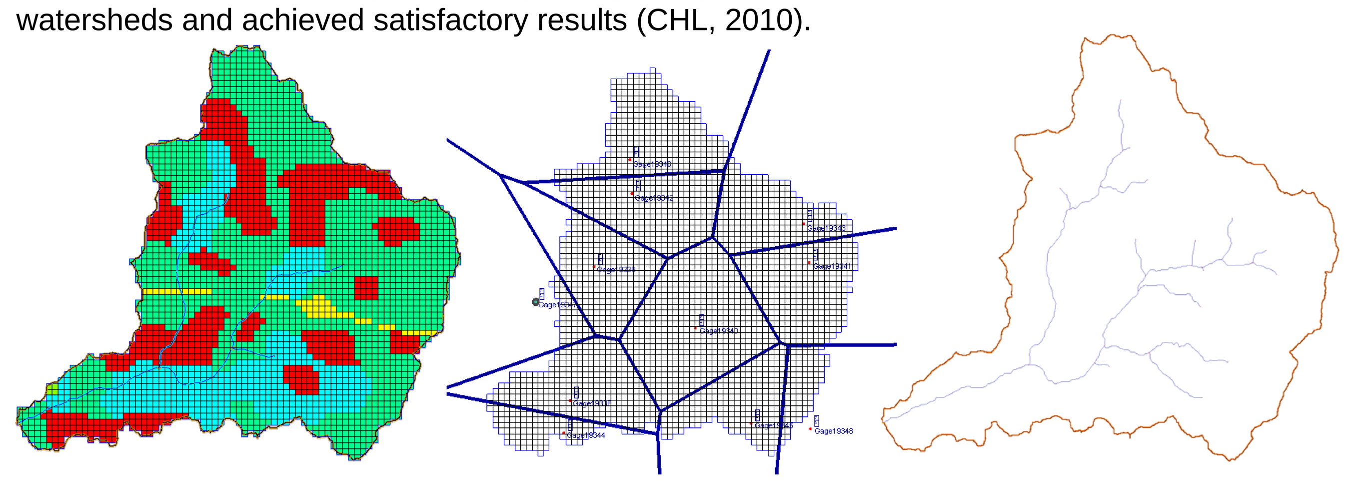


For in-stream water quality modeling it is assumed that longitudinal and temporal changes (1D transport) are applicable. Water quality is affected in streams due to physical transport and exchange processes and biological, chemical, and biochemical kinetic processes along with changes due to benthic sediments. Currently, the in-stream water quality module includes a set of NSM. In-stream water quality kinetics computes algal biomass, organic and inorganic nitrogen and phosphorus species, CBOD and DO. The schematic representations of in-stream water quality processes with NSM I and NSM II are shown the following figure.



2 Hydrologic Simulation

GSSHA is a reformulation and enhancement of the CASC2D. The model incorporates 2D overland flow, 1D stream flow, 1D unsaturated flow and 2D groundwater flow components. The GSSHA model employs mass conservation solutions of partial differential equations and closely links the hydrologic components to assure an overall mass balance. GSSHA had already been tested and applied for hydrologic response and sediment transport in several watersheds and achieved satisfactory results (CHL, 2010).



The modeling of hydrologic processes begins with rainfall being added to the watershed, some of which is intercepted by the canopy cover, evapotranspirated or infiltrated. Hydrologic processes that can be simulated and the methods used to approximate the processes with the GSSHA model are listed in Table 1.

Table 1 Processes and approximation techniques in the GSSHA model

Process	Approximation
Precipitation distribution	Thiessen polygons (nearest neighbor) Inverse distance-squared weighting
Snowfall accumulation and melting	Energy balance
Precipitation interception	Empirical two parameter
Overland water retention	Specified depth
Infiltration	Green and Ampt (GA) Multi-layered GA Green and Ampt with Redistribution GAR) Richard's equation (RE)
Overland flow routing	2-D diffusive wave
Channel routing	1-D diffusive wave, 1-D dynamic wave
Evapo-transpiration	Deardorff Penman-Monteith with seasonal canopy resistance
Soil moisture in the vadose zone	Bucket model RE
Lateral groundwater flow	2-D vertically averaged
Stream/groundwater interaction	Darcy's law
Exfiltration	Darcy's law

3 Soil Erosion and Sediment Transport

The sediment algorithm is included in GSSHA and invoked only when sediment simulation is required. The sediment module is designed for estimating sediment delivery and channel transport in watersheds. The overland sediment transport is based on a 2D mass balance equation:

$$\frac{\partial(hc)}{\partial t}+\frac{\partial(cq_x)}{\partial x}+\frac{\partial(cq_y)}{\partial y}=e(x,y,t)+q_z(x,y,t)$$

Modified Kilinc-Richardson equation is used within each model grid cell in two dimensions to compute the transport capacity of sediments on the overland flow plane :

$$q_{sx}=25500p^{2.035}S_{fx}^{1.664}\frac{K*C*P}{0.15}\qquad q_{sy}=25500q^{2.035}S_{fy}^{1.664}\frac{K*C*P}{0.15}$$

Where where h = water depth (m); c = sediment concentration (kg m^{-3}); t = time (s), q_x and q_y = unit discharge in x- and y-directions, respectively (m^2/s); and $e(x,y,t)$ = sediment source/sink (kg m^{-2}• s^{-1}); $q_z(x,y,t)$=lateral sediment inflow to the channels (m^{-2} s^{-1}).

The channel sediment transport is based on a o1D mass balance equation:

$$\frac{\partial(hc)}{\partial t}+\frac{\partial(cq_x)}{\partial x}+\frac{\partial(cq_y)}{\partial y}=e(x,y,t)+q_z(x,y,t)$$

The Engelund-Hansen relation is used to calculate sediment transport for each sediment size class and the resulting total transport is calculated by multiplying the proportion of the size in the parent material by the calculated rate.

$$G_i=KF_i\frac{0.05\,BV^2h^{3/2}S^{3/2}}{(s-1)^2D_i\sqrt{g}}$$

where G_i is the volumetric sediment transport rate of i^{th} size fraction (m^3 s^{-1}), K is the calibration coefficient (=1 for standard equation), F_i is the proportion of i^{-th} faction in the parent material or deposited layer, B is the width of flow (m), V is the mean water velocity (m s^{-1}), h is the flow depth (m), S is the water surface slope, s is the specific gravity of i^{th} fraction, and g is the gravitational acceleration (m s^{-2}), is the sediment density (kg m^{-3}), is the water density (kg m^{-3}), D_i is the mean size of i^{-th} fraction (m). The factor 0.05 in the equation was developed from empirical data.

5 Coupling Hydrology, Sediment and Nutrient Simulation Modules

Mass Transport

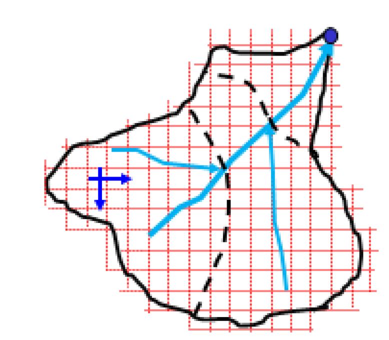
$$\frac{\partial(V\cdot C_j)}{\partial t}+L(C_j)=\sum R_{j,k}+\sum S_j$$

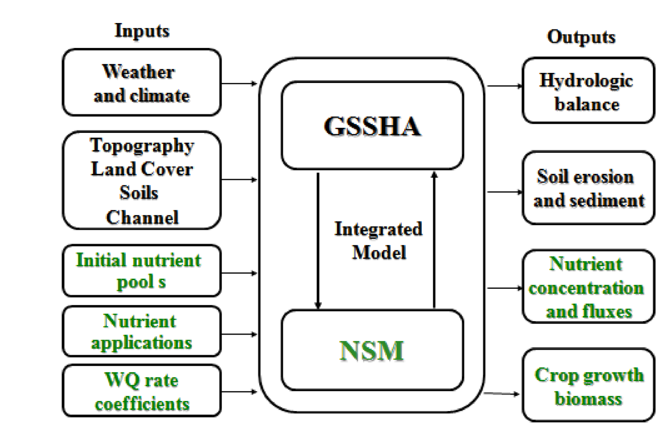
Mass Transfer between the Upper Sediment Layer and Water Column

$$S_d=A\cdot k_e\left(C_{d2}/\phi-C_d\right)$$

Erosion and Sedimentation

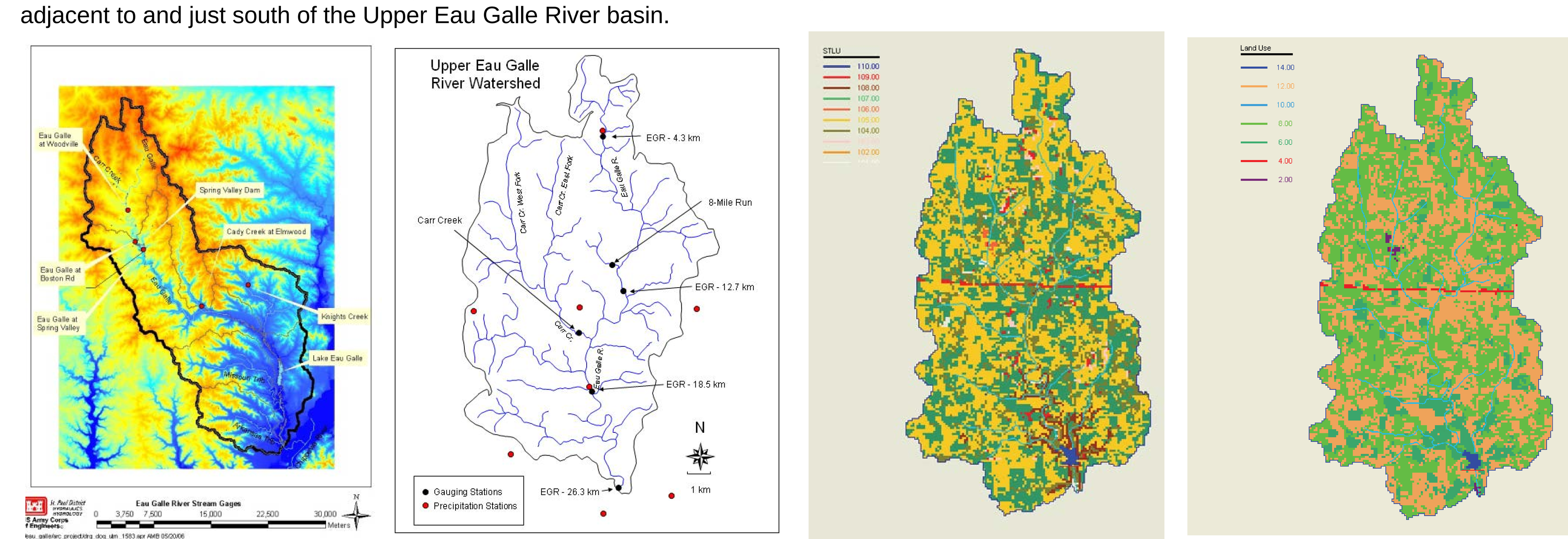
$$S_r=A\sum_{n=1}^{N}f_p^n v_r^n C_{s2}^n\qquad S_s=A\sum_{n=1}^{N}f_p^n v_s^n C_s^n$$





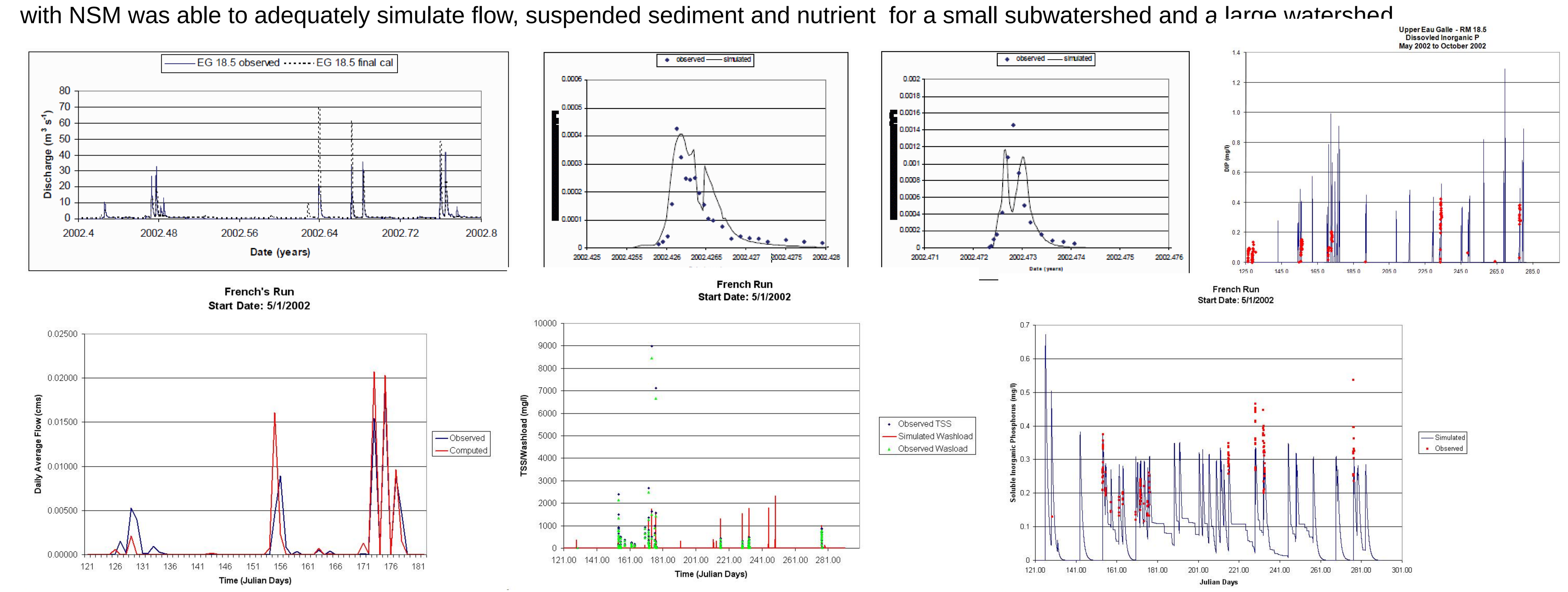
6 Model Validation and Application

There were concerns about the effects of land use change on hydrologic and water quality conditions in the larger Eau Galle River system. Two case studies were conducted to validate the nutrient transport and cycling processes and integration with hydrologic and sediment components at Eau Galle Watershed. The Eau Galle Watershed encompasses a 402 km^2 area in northwest Wisconsin. The upper portion of the watershed, that portion above Spring Valley Dam, has been the subject of intensive past studies, and is relatively data rich. In addition to the concern about agricultural effects on water quality in the lake and river. Hydrology, soil erosion, nutrient transport and export were examined at the Upper Eau Galle River watershed and at one sub-watershed at an adjacent watershed (French Creek). The French's Run study site was located in the headwaters of French Creek watershed, which is adjacent to and just south of the Upper Eau Galle River basin.



The land use and soil type maps are shown in above figures. The land uses includes residential, commercial, forest, grass, wetland, row crop, and open water. The predominate land uses in the watershed are pasture (8, light green) and row crops (12, beige). Land use in the Franch Run subwatershed was dominated by corn production during the study period There is a moderate amount of forest (6, dark green), with limited residential and commercial use. The predominant soil type is silty loam.

Results of the model calibration for flow, suspended sediment, and water quality at the USGS gauge (EG 18.5) and French Run during the period June through October 2002 are shown in the following figures. The mean absolute error (MAE) of the larger two peaks is 3 percent of the observed at the Upper Eau Galle River watershed. The error in total discharge is 1.5 percent of observed. The hydrograph shapes and base flow are accurately reproduced. Three sediment size fractions were simulated, sand, silt, and clay. The model was calibrated to two observed events that occurred in June 2002 The MAE for the total sediment discharge (m^3) for the two events was 12 and 4 percent of the observed, respectively. In general, the sediment calibration and verification results are good. The model calibration for water quality was conducted only for dissolved N and P at gages where observed data were available. These results indicate that the trend of modeled nutrient concentration match with the trend of the measured data. Overall GSSHA with NSM was able to adequately simulate flow, suspended sediment and nutrient for a small subwatershed and a large watershed



7 Summary

The GSSHA model with nutrient simulation module (NSM) was applied to both a small subwatershed and a large watershed. The model was able to adequately simulate hydrology and sediment transport in both watersheds as seen by the calibration. GSSHA also demonstrated its capabilities in simulating the fate and transport of nutrients at the watershed scale as well. The resulting physically based distributed water flow, sediment and nutrient transport and fate modeling system is capable of assessing hydrology and transport and fate of sediments and nutrients across the landscape within the watershed due to changing land uses and implementation of best management practices. Future research and development efforts will continuously improve the water quality kinetics within NSM and linkage within GSSHA.