Report as of FY2007 for 2007MI103B: "Evaluation of SWAT and HIT Models in the Kalamazoo River Watershed, Michigan"

Publications

Project 2007MI103B has resulted in no reported publications as of FY2007.

Report Follows

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Project Class: Research

Problem and Research Objectives

Sediment contribution to lakes and streams is a complex problem that has negative impacts on everything from fish and animal habitat to local and federal economies. While substantial strides have been made in recent decades to reduce point source pollution to our waterways, non-point pollution continues to be a significant source of sediment in lakes and streams and the cause of many water quality issues in the Great Lakes region. Erosion run-off from agricultural areas often carries harmful nutrients, such as phosphorus and nitrogen, which severely damage the macro invertebrate populations in waterways. This in turn disrupts the food chain in our aquatic and terrestrial systems near the waterways. Concentrations of nutrients in lakes can also lead to eutrophication, decimating lake ecosystems. While habitat disruption is one example of the chemical consequences of excessive sediment contribution, the physical space sediments take up within waterways can have significant economic costs. The U.S. Army Corps of Engineers spends over $20 million a year on sediment dredging in the Great Lakes region alone (Ouyang et al., 2005). Furthermore, decreased navigability of streams and lakes hurts everything from international trade via large commercial boats to local recreation revenues via canoes and fishing. As a predominantly agricultural watershed, the Kalamazoo River Watershed in southwest Michigan is susceptible to these challenges and provides an ideal environment to compare and evaluate models designed to quantify these threats.

Multiple models have been developed to quantify nutrient loading, identify particular sub-watersheds that have the highest rates of contribution, and even generate spatially distributed risk maps with farm-level resolution. Two models in particular are SWAT (Soil and Water Assessment Tool) and HIT (High Impact Targeting). SWAT is a spatially-lumped model that can provide predictions of specific nutrient contributions (such as phosphorus and nitrogen) within a watershed. HIT is a spatially-distributed model and can provide-farm level estimates of sediment contributions to a watershed's stream network. These models can help address the problem of non-point source pollution, but their reliability depends on the availability of monitoring data. SWAT is able to run without monitoring data, but its reliability is significantly enhanced when the monitoring data is used to calibrate the model. HIT, on the other hand, does not incorporate such data, but its reliability has not been fully evaluated due to a lack of monitoring data availability. SWAT and HIT both have unique strengths that could complement each other (the breadth of SWAT's output and the detailed resolution of HIT), but without

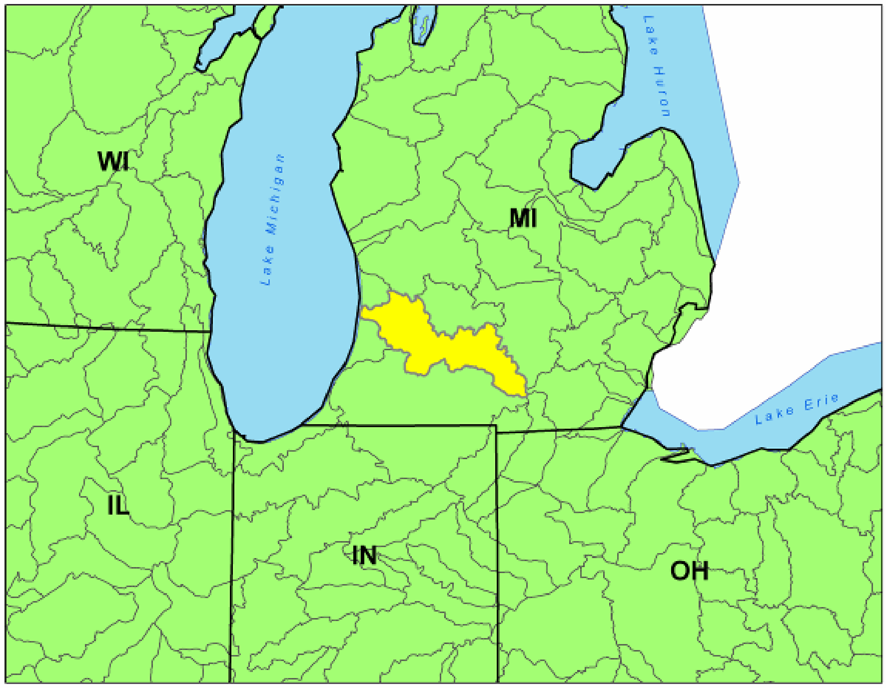

Figure 1. 8-digit HUCs of the lower Great Lakes Basin. Kalamazoo highlighted in yellow.

detailed and consistent monitoring and an evaluation of their respective effectiveness their use in tandem would be questionable. (Neitsch et al., 2002)

The primary objective of this project was to evaluate the ability of the HIT and SWAT models to reliably quantify nutrient loading in the Kalamazoo River Watershed by comparing model results to stream monitoring data provided by Michigan State University's Kellogg Biological Station. The project's sub-objectives included the following: calibrating each model to reliably predict nutrient loading in the Kalamazoo and topographically similar watersheds; evaluating each model within topographically unique sub-watersheds to determine whether one model is better suited to predict nutrient loading under certain conditions.

Methodology

HIT Modeling

HIT was run for Michigan's Kalamazoo River Basin (Figure 1), and clipped to basin boundary for where monitoring data present (Figure 2). HIT represents the combination of two models, the Revised Universal Soil Loss Equation (RUSLE) (Renard, et al., 1997) and the Spatially Explicit Delivery Model (SEDMOD) (Fraser, 1999). RUSLE yields an annual estimate of sheet erosion while SEDMOD outputs a delivery ratio indicating the percentage of eroded soil that reaches the stream network. When combined, the two models produce an annual estimate of sediment loading. To calculate RUSLE and SEDMOD for the Kalamazoo, the necessary inputs were gathered (Table 1) and, where necessary, converted to grid datasets to be analyzed in a GIS. The end result was a spatially explicit sediment loading map (Figure 3) where each pixel contained an estimate of annual sediment loading to streams for a given 900 meter² area. This raster was subsequently clipped by the boundaries of the sub-basins output by the SWAT analysis of the Kalamazoo. Total annual sediment loading and sediment loading per acre, as estimated by HIT, were then calculated for each of the sub-basins.

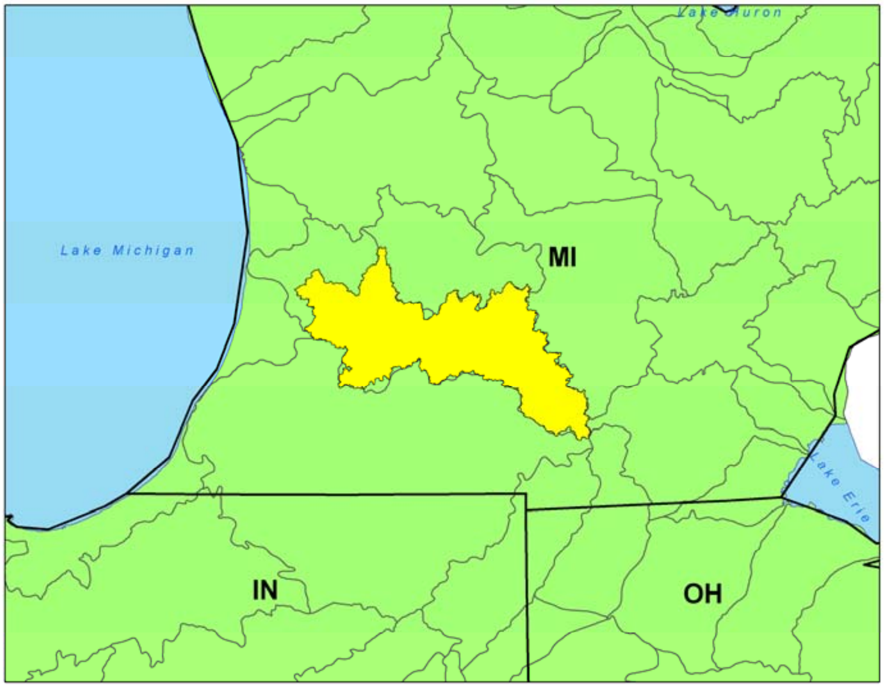

Figure 2. Basin (in yellow) captured by the KBS Monitoring**.**

Table 1. HIT Inputs

Dataset	Data Source	Format	RUSLE use	SEDMOD use
Digital Elevation Model	USGS National Elevation Dataset – 1 arc second (30-meters) (usgs.ned.gov)	Raster	LS factor (steepness)	Derive overland flow, distance to stream network.
Land cover	2001 National Land Cover Dataset (mrlc.gov)	Raster	C factor (cover management)	Surface roughness
Crop Type / Tillage	CTIC Crop Residue Management Survey	Table	Weight C factors by county-level crop type and tillage practice.	
Soils	USDA SSURGO soil surveys	Vector	K factor (soil erodibility)	Clay content
Precipitation	US EPA, Oregon State University, Illinois State University, PRISM Model	Raster	R factor (rainfall erosivity)	
Streams/Rivers	USGS National Hydrography Dataset (high resolution)	Vector		Location of stream networks
Watershed Boundary	NRCS Watershed Boundary Dataset	Vector	Used to clip RUSLE inputs.	Used to clip SEDMOD inputs

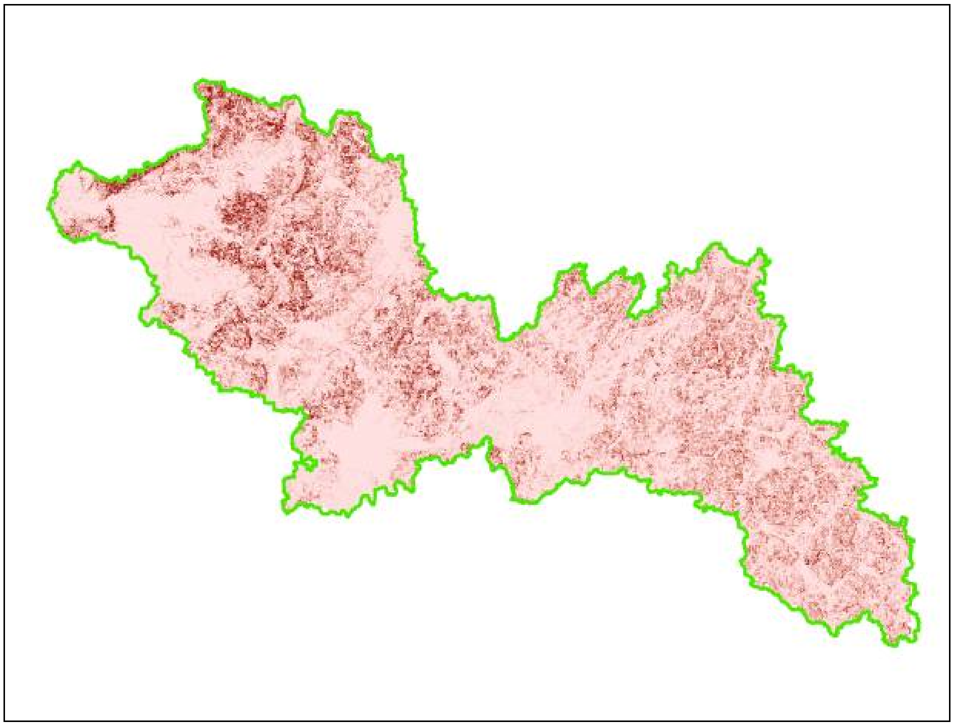

Figure 3. HIT sediment loading risk map of the Kalamazoo River Watershed.

SWAT Modeling

The Soil and Water Assessment Tool (SWAT) simulation model was developed by the USDA Agricultural Research Service's Grassland, Soil and Water Research Lab in Temple, Texas. The model was developed for the purpose of assisting water resource managers in predicting and assessing the impact of management on water, sediment, and agricultural chemical yields in large, ungaged watersheds. The hydrologic components of the model have been rigorously tested on watersheds of varying size (Arnold et al., 2000; Srinivasan et al., 1998). The basic model operates on a daily time step and allows continuous simulation over many years. Recent additions allow for simulating surface runoff and infiltration using the Green and Ampt approach using rainfall data of anytime increment and hourly channel routing. The SWAT model has eight major components: hydrology, weather, erosion and sedimentation, soil temperature, plant/crop growth, nutrients, pesticides, and agricultural management.

To simulate the spatial heterogeneity of land cover, topography, soil type and climate, the watershed is subdivided into a number of user-delineated sub-basins. Each sub-basin is then further subdivided into individual Hydrologic Response Units (HRU) which is an individual combination of landuse/cover/management, soil type and meteorological data.

The daily or sub-daily water budget is computed for each HRU in the watershed. Daily surface runoff is calculated using the SCS curve number approach or on an hourly basis using the Green and Ampt method. Peak runoff rate is calculated using a modified rational formula and the routing of in-channel flow between sub-basins is computed with Manning's equation and the Muskingum or Variable Storage Method.

Several sets of inputs are required to run the model (Table 2). Basic inputs into the model include a 30-m digital elevation model (NED – same as HIT, see Table 1), STATSGO soils coverage, and 2001 Michigan land cover/land use data (NLCD – same as HIT, see Table 1). Observed weather data used in the model was a combination of NOAA cooperative rain gauges used for fallow season simulation and sub-basin averaged NEXRAD derived precipitation estimates for the growing season simulation.

The model was run under two scenarios; 1) using observed weather data during the period of 2003 through 2006 to compare to the observed Phosphorus data and 2) using synthetic weather data over a 20 year period to compare the long term average sediment delivery from SWAT to the HIT model.

To calibrate the SWAT model to the hydrology of the river the USGS stream gaging station on the Kalamazoo River near Battle Creek (Gauge Station 04105500) was used. To calibrate the hydrology portion of the model, the primary variables that were adjusted was the NRCS curve number for the runoff volume and peak flow and the amount of wetlands within the watershed. The Kalamazoo River and many of its tributaries flow through riparian wetlands which have a great buffering capacity for peak flow rates that exceed the capacity of the main channel.

Stream Monitoring

Intensive phosphorus sampling was performed on the Kalamazoo River from 5/10/2005 – 10/4/2006 and 4/4/2006 – 9/27/2006 as part of the Lake Allegan/Kalamazoo River Watershed TMDL project. Weekly water samples were collected from the thalwag portion of the stream using a Van Dorn horizontal sampler at 13 locations in 2005 and 15 locations in 2006. Samples were filtered using a 0.45 μm filter. Unfiltered samples were analyzed for total phosphorus and filtered samples for total dissolved phosphorus. Phosphorus was determined using the persulfate digestion and colorimetric method.

Growing season total and dissolved phosphorus loadings were calculated for the monitored watersheds. Daily discharge for the load calculations were obtained from the SWAT model runs, providing a common discharge basis for comparing actual to modeled phosphorus loading. The availability of daily discharge and weekly phosphorus concentrations presents some challenges in calculating an unbiased estimate of load. The Beale Ratio Estimator which has been used widely in Great Lakes loading calculations, thoroughly discussed in Baun (1982), was used for load calculations. Ratio estimators use the period's data to calculate a mean daily load, then uses the mean discharge from days lacking concentration data to adjust the mean daily load (Richards, 1998). AutoBeale, a computer implementation of the Beale Ratio Estimator, iteratively seeks out the discharge stratification and minimizes the variance of the load estimate for a given set of data. The AutoBeale program was used for the load calculations for this study.

Calibration of SWAT using Monitoring Data

Multiple iterations of SWAT modeling were conducted in an effort to match SWAT estimates of total phosphorus loading to values estimated by the monitoring data and AutoBeale program. The presence of several significant impoundments, particularly Morrow Lake, within the watershed proved challenging to SWAT. After several unsuccessful attempts to reconcile SWAT's total phosphorus with the AutoBeale estimates, we chose to move the calibration and

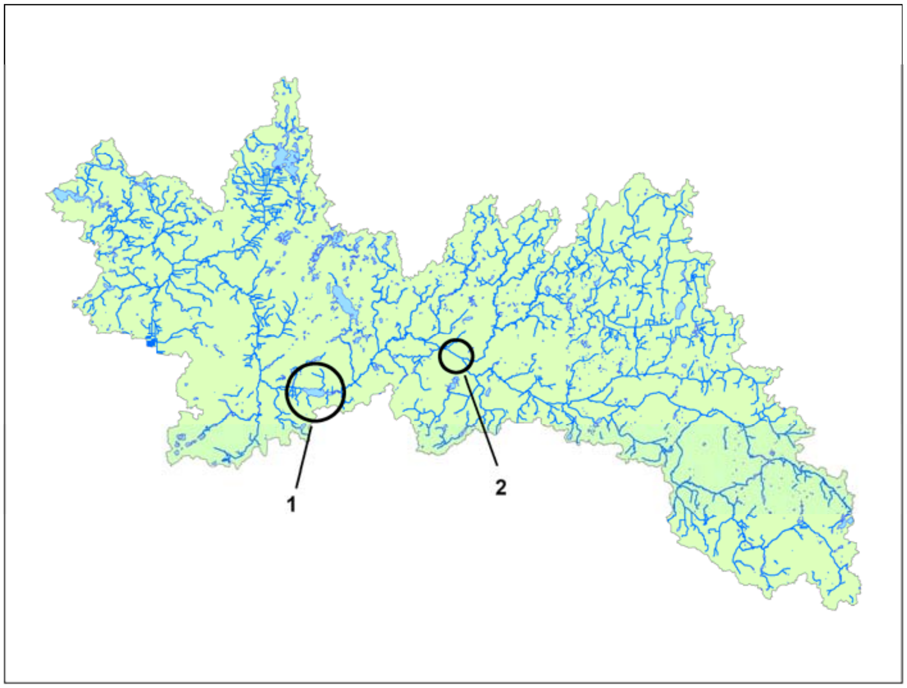

Figure 4. Monitoring basin and hydrography.
1. Lake Morrow impoundment.
2. Upstream monitoring station used for final analysis.

analysis upstream from the problem impoundments (Figure 4). This necessitated a new SWAT run and new study area boundaries, as output by SWAT (Figure 5). HIT could not be directly calibrated to the monitoring data because HIT's output is total sediment loading to streams and the monitoring data did not measure total suspended sediment. This project sought to evaluate HIT sediment estimates using SWAT's total sediment and total phosphorus estimates (phosphorus was captured in monitoring data) as a proxy. This assumed a positive direct relationship between in-stream phosphorus and sediment, which previous studies have shown (Varnakovida, et al. 2005; Mau & Christensen 2001).

Comparison of SWAT and HIT

Once a SWAT output of total phosphorus was as calibrated with the monitored estimate as could be achieved, the SWAT sediment loading estimate was compared to HIT's. Sub-basin sediment loading rates in metric tons per hectare were calculated for each sub-basin. Correlations of these rates were analyzed, and a regression analysis was performed to attempt to explain the differences between the models' rates in terms of land cover class percentages, soil type, topography, sub-basin size, and topography. The Analytical Tools Interface for Landscape Assessments (ATtILA) (http://www.epa.gov/esd/land-sci/attila/index.htm) was utilized to extract, for each sub-basin, land cover class percentages from the NLCD, soil texture from the SSURGO soils dataset, and slope from the DEM.

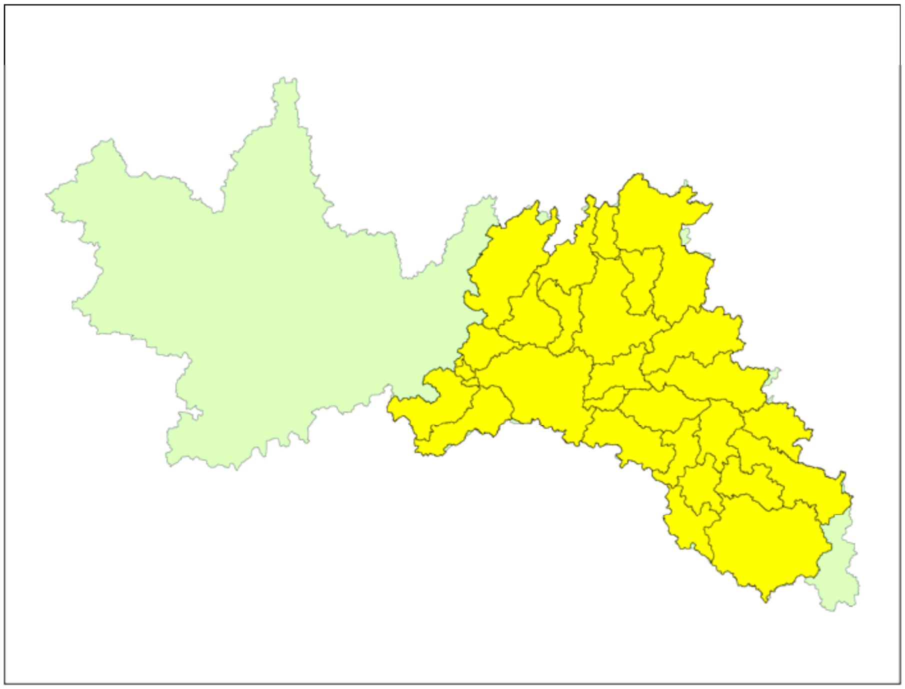

Figure 5: Final SWAT study basins (in yellow) within the original monitoring basin.

Principal Findings

Calibration of SWAT using stream monitoring data

For the growing seasons of 2005 and 2006 the AutoBeale program estimated annual phosphorus loading at the monitoring station (location 2 in Figure 4) at 4,758 kg and 6,539 kg respectively. SWAT estimates of annual phosphorus location at the same location and for the same time period were 8,319 kg and 11,714 kg respectively. Though these raw numbers are significantly different, the temporal trends they reflect are closely similar. The monitored phosphorus increased from 2005 to 2006 by 37%, while SWAT estimated an increase of 41%. The difference in the raw numbers could have been the result of relatively short time period. A two-year simulation will make SWAT more sensitive to peak events and increase the likelihood of overestimates. Additionally, the differences could have resulted from physical features that were not captured within the SWAT inputs. Best management practices (BMPs) that reduce run-off may have been in place within the study basin, but not reflected in the land cover input (NLCD 2001). SWAT's accurate representation of the temporal trend in phosphorus loading could imply that its prioritization of sub-basins (by sediment loading rate) is accurate and could be reliably compared to HIT's. However, until SWAT can be calibrated against a longer record of monitoring data, the use of SWAT's sediment estimate as a proxy for an evaluation of HIT in this area should be viewed with caution.

Comparison of SWAT and HIT estimates

For the entire study basin, SWAT estimated a total annual sediment loading of 33,549 metric tons. This amount represents sediment transport to streams (as calculated by USLE), not to the watershed outlet; therefore it does not reflect the effect of bank erosion or in-stream deposition. HIT's estimated

47,280 annual metric tons of sediment loading to streams for the study basin, which also does not include bank erosion or in-stream deposition.

Since both SWAT and HIT fundamentally rely on USLE (HIT uses RUSLE) the initial expectation was that the models' use of different methods for calculating sediment delivery was the primary cause for the difference in annual estimated totals. HIT employs SEDMOD to calculate spatially explicit delivery ratios while SWAT uses the MUSLE equation which is:

$$Sediment = 11.8(Q_{surfacerunoff} * q_{peakrunoffrate} * Area_{HRU})* K_{USLE} * C_{ULSLE} * P_{USLE} * LS_{USLE} * CFRG$$

where *Sediment* is the sediment yield on a given day (metric tons), Q_{surf} is the surface runoff volume (mm H_2O/ha), q_{peak} is the peak runoff rate (m^3/s), $area_{hru}$ is the area of the HRU (ha), K_{USLE} is the USLE soil erodibility factor (0.013 metric ton m^2 hr/(m^3-metric ton cm)), C_{USLE} is the USLE cover and management factor, P_{USLE} is the USLE support practice factor, LS_{USLE} is the USLE topographic factor and *CFRG* is the coarse fragment factor. USLE predicts average annual gross erosion as a function of rainfall energy. In MUSLE, the rainfall energy factor is replaced with a runoff factor. This improves the sediment yield prediction, eliminates the need for delivery ratios, and allows the equation to be applied to individual storm events. Sediment yield prediction is improved because runoff is a function of antecedent moisture condition as well as rainfall energy. Delivery ratios (the sediment yield at any point along the channel divided by the source erosion above that point) are required by the USLE because the rainfall factor represents energy used in detachment only. Delivery ratios are not needed with MUSLE because the runoff factor represents energy used in detaching and transporting sediment.

One of the primary objectives of this project was to determine if HIT and SWAT similarly prioritize sub-basins in terms of sediment loading, and could therefore potentially be used in tandem. Therefore, a detailed analysis on sediment loading rates for the study area's 29 sub-basins (Figure 5) was performed. HIT's sediment loading rates ranged form 0.001 to 0.394 metric tons per hectare, with a mean of 0.209 m.t./ha; SWAT's rates ranged from 0.023 to 0.297 m.t./ha, with a mean of 0.151 m.t./ha. The rates were significantly positively correlated ($r = 0.80$). The results were slightly different when the rankings of sub-basins were analyzed. SWAT and HIT rankings were again significantly positively correlated, but at a lesser $r = 0.52$ (Spearman rank correlation). Sub-basin ranks are important to typical users of SWAT and HIT as sediment loading rates are utilized to prioritize regions for conservation efforts, such as a state agency or local conservation district looking to target nutrient run-off reduction programs. The lower rank correlation implies that, in some areas, SWAT and HIT may send users different messages.

In an effort to explain this variability, differences between SWAT's and HIT's sediment loading rates were calculated (HIT rate minus SWAT rate) for each sub-basin. Values ranged from -0.037 to 0.172 m.t./ha, with a mean of 0.058 m.t./ha. These differences were compared against land cover class percentages, soil types, basin size, basin sediment delivery ratio, and topography in a stepwise regression analysis. Regression models were tested utilizing various permutations and transformations of the following terms:

- %agriculture
- %pasture
- %row-crops
- %urban
- %forest
- %wetland
- %sand soils
- %silt soils

- %clay soils
- mean delivery ratio
- mean RUSLE R
- mean RUSLE K
- mean RUSLE C
- mean RUSLE LS
- mean slope
- hectares

The different methods of representing sediment transport in SWAT and HIT proved not to be statistically significant ($r^2 = 0.27$), contrary to initial expectations from the analysis of SWAT and HIT estimates of sediment loading totals. The strongest model was simply a function of row-crop land cover:

*Sediment Loading Rate Difference (HIT - SWAT) = -0.0069 + 0.0018 * Percent Row-crop (2001 NLCD class 82)*

$\beta_{\text{Percent Row-crop}}$ and F-statistic are both significant at the 99% confidence interval.
$\beta_{\text{Percent Row-crop}}$ adjusted to account for spatial-autocorrelation.
$R^2 = 0.34$

The model's R^2 is not particularly strong in its own right, but was stronger than the other possible models. The positive sign of $\beta_{\text{Percent Row-crop}}$ indicates that HIT sediment loading rates exceed those of SWAT in areas dominated by row-crop agriculture. Within HIT, such areas receive the highest values for RUSLE's C factor, and represent areas of decreased surface roughness (facilitating sediment transport to streams). This could imply that there are potentially significant differences between how HIT and SWAT represent C factor, and how land cover factors into sediment transport within each of the models. Additional analyses of HIT and SWAT are needed. Independent comparisons of erosion estimates (USLE and RUSLE, without factoring in sediment transport) and sediment transport (SWAT'S use of MUSLE and HIT's use of SEDMOD) may illuminate the sources of these differences in rates, and help explain the larger differences in total sediment loading. Additionally, further effort to calibrate SWAT (longer monitoring record, BMP locations) and HIT estimates to in-stream monitoring should yield greater confidence in an analysis of the models' differences.

Significance

This project represented the first concerted effort to compare SWAT and HIT. The two models each have their own strengths. SWAT produces detailed outputs on nutrient loading, while HIT produces spatially explicit maps of sediment loading. The two could potentially be used together to provide a rich product, useful to many in the conservation community. However, if the two models tell different stories regarding sediment loading within a watershed, then a combination of the two could be suspect. This project established a positive correlation between the different models' prioritization of sub-basins by sediment loading rates, but a weak positive correlation in their rank correlations. Prioritization at the watershed scale is important to managing agencies currently using these tools, such as the Michigan Department of Agriculture and the USDA Natural Resource Conservation Service. This project did show relatively large discrepancies between the models in terms of total estimated sediment loading, and was not able to fully explain the models' differences in sediment loading rates. This could have been the result of an inability to confidently calibrate the two models and/or the way to the two models treat land cover. But this effort served as a solid initial analysis, and identified potential sources of discrepancy between the two models that warrant further analysis.

References

Arnold, J.G., R.S. Muttiah, R. Srinivasan, and P.M. Allen. 2000. Regional estimation of base flow and groundwater recharge in the upper Mississippi basin. *J. Hydrol.* 227(2000): 21 40.

Baun, K. 1982. Alternative Methods of Estimating Pollutant Loads in Flowing Water. Tech. Bulleting 133, Dept. Natural Resources, Madison Wisconsin. 11 Pages.

Fraser, Robert. *SEDMOD: A GIS-based Delivery Model for Diffuse Source Pollutants* (doctoral dissertation). Robert Fraser, Yale University. May 1999.

Keiser and Associates. "SWAT Modeling of the St. Joseph River Watershed, Michigan and Indiana." Prepared for the Friends of the St. Joseph River. Kalamazoo, Michigan. June 2005.

Mau, D.P, Christensen, V.G. Reservoir sedimentation studies to determine variability of phosphorus deposition in selected Kansas watersheds: in Proceedings of the Seventh Federal Interagency Sedimentation Conference, March 25-29, 2001, Reno, Nevada. Subcommittee on Sedimentation, v. 2, IX-28 to IX-34a. (online linkage: http://ks.water.usgs.gov/Kansas/pubs/reports/mau.fisc.html)

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., King K.W. *Soil and Water Assessment Tool Theoretical Documentation.* Grassland, Soil and Water Research Laboratory, Agricultural Research Service. Temple, TX 2002

Renard, Foster, Weesies, McCool, Yoder. *Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE)* USDA, Agriculture Handbook Number 703. 1996.

Richards, R.P. 1998. Estimation of Pollutant Loads in River and Streams: A guidance document for NPS Programs. Project report prepared under Grant X998397-01-0, U.S. Environmental Protection Agency, Region VIII, Denver. 108 p.

River Raisin Watershed Council Newsletter, Fall 2006. River Raising Watershed Council. Accesed January 2007. (online linkage: http://riverraisin.org/newsletter/fall_2006/swat2.doc.)

Srinivasan, R.S., J.G. Arnold, and C.A. Jones. 1998. Hydrologic modeling of the United States with the soil and water assessment tool. *Int. J. Water Resour. Dev.* 14(3): 315-325.

Varnakovida, P., Wiangwang, N., Messina, J.P. "Simulation of Lake Nitrogen, Phosphorus and Sediment Levels Based on Land Use/Land Cover Type and Pattern." Geoscience and Remote Sensing Symposium, 2005. IGRASS '05, Proceedings. 2005 IEEE International. July 25-29, 2005. Volume 7, p. 4545-4548. Date Published in Issue: November 14, 2005.