Model Development and Applications at the USDA-ARS National Soil Erosion Research Laboratory

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ABSTRACT

The United States Department of Agriculture (USDA) has a long history of development of soil erosion prediction technology, initially with empirical equations like the Universal Soil Loss Equation (USLE), and more recently with process-based models such as the Water Erosion Prediction Project (WEPP). This presentation will highlight past, current, and future water modeling activities at the National Soil Erosion Research Laboratory (NSERL) of the USDA's Agricultural Research Service (ARS), located in West Lafayette, Indiana on the campus of Purdue University. Recently a new five-year plan of research for water quality projects at the NSERL was approved, with several components related to model development and applications. In addition to continued maintenance and application of WEPP, other activities include development of a WEPP-Water Quality model, completion of a combined wind and water erosion model, application of the APEX and SWAT models to NSERL research watersheds, and evaluation of climate change utilizing various modeling approaches. Also as part of the water quality research at the NSERL, the laboratory conducts extensive watershed monitoring in northeastern Indiana, at scales ranging from 2 to 19,000 hectares, measuring flow, nutrient, and pesticide losses. Measurements go back almost ten years, providing a rich database for testing, calibration, and validation of watershed water quality models at multiple scales. Some facets of NSERL research include use of measured soil moisture data in the watersheds with data assimilation techniques to enhance SWAT model predictions, with hopes in the future to also utilize remotely-sensed soil moisture. WEPP model enhancements include expansion of web-based GIS interfaces, expanded crop management databases, improved watershed channel hydrology and channel erosion options. Cooperative projects with other researchers will include evaluation and improvement of the tile drainage hydrology component of the WEPP model, and updating of the code to allow simulation of the impacts of global change and carbon dioxide enrichment of the atmosphere. Climate change studies planned will utilize GEM (Global Environmental Models) and downscale their predictions of changes in temperatures, precipitation, and atmospheric CO_2 content to the watershed and hillslope scales common in WEPP and other models.

INTRODUCTION

Prediction of soil erosion by water for use in conservation planning was the main reason for the establishment of the ARS research unit at Purdue University in West Lafayette, Indiana in 1954. Thousands of plot-years of runoff and soil loss data from natural runoff plots and small watersheds at the soil conservation experiment stations (SCES) of the USDA Soil Conservation Service (SCS) were sent to the ARS National Runoff and Soil Loss Data Center (NRSLDC) at Purdue, and the data transferred to computer punch cards (Gilley and Flanagan, 2007). Statistical analyses were then conducted on the large dataset using the new computer technology available at the university, ultimately resulting in the development of the Universal Soil Loss Equation (USLE), which was subsequently implemented by SCS across the U.S. (Wischmeier and Smith, 1961, 1965, 1978).

New erosion modeling techniques were proposed by NRSLDC scientists in the late 1960's (Meyer and Wischmeier, 1969; Foster and Meyer, 1972). The erosion component of the Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS, Knisel, 1980) model was developed by Foster et al. (1980), and it was subsequently used in the GLEAMS (Groundwater Loading Effects of Agricultural Management Systems) model (Leonard et al., 1987).

The USDA-ARS National Soil Erosion Research Laboratory (NSERL) was constructed on the campus of Purdue University to house the federal scientists there from the NRSLDC who continued to conduct soil erosion research. The building was dedicated in 1982, with initial research efforts heavily related to fundamental soil erosion process mechanics, soil sealing and crusting processes, sediment transport, and soil erosion prediction technology development. Over the past 30 years, the research studies conducted at the NSERL have expanded from solely soil erosion on uplands to now include soil quality, hydrology, erosion, and chemical transport processes at plot, field, and watershed scales. Development of erosion prediction computer simulation models began in the 1970's and continues today.

In 1985, two major erosion modeling efforts were begun at the NSERL: the Revised Universal Soil Loss Equation (RUSLE), and the Water Erosion Prediction Project (WEPP). RUSLE was intended to be a short-term project to update the empirical USLE technology with the most current databases (climate, soils, etc.) and to provide a computerized version of the equation (Renard et al., 1991). WEPP (Laflen et al., 1991) was to be new process-based erosion prediction technology, simulating hydrology, erosion, sediment transport and deposition, and a variety of associated processes (plant growth, residue decomposition, etc.). RUSLE was initially developed at the NSERL, but then responsibilities were transferred to ARS locations in Tucson, Arizona, then Oxford, Mississippi. WEPP development involved a large team of federal and university scientists and students and user agency (SCS, FS – Forest Service, and BLM – Bureau of Land Management) staff across the U.S., with field experimentation and main model development occurring from 1985-1995 (Flanagan et al., 2007). WEPP model maintenance and development work continue at the NSERL, and will be discussed in this paper.

The NSERL also expanded its research focus in 2002 when it began to monitor watersheds in northeastern Indiana for agricultural chemicals that were finding their way into the drinking water supply for the city of Fort Wayne (Flanagan et al., 2003). A number of ditch and field sampling stations have been instrumented, and an extremely large database has been created tracking flow discharge, herbicides (Pappas et al., 2008; Pappas and Huang, 2008), and nutrients (Smith et al., 2008). Modeling studies have also been conducted using these watersheds and data, and will be discussed later in this article.

In 2011, the four main research projects at the NSERL were revised and consolidated into two new initiatives. These two are entitled "Biogeochemical processes and soil management impacts on soil erosion, soil/air/water quality, and greenhouse gas emissions" which is under the ARS National Program (NP) 212 on Climate Change, Soils, and Emissions, and "Assessing conservation effects on water quantity and quality at field and watershed scales" which is under the ARS NP-211 on Water Availability and Watershed Management. Research on the development and application of erosion prediction and water quality models at the NSERL falls within the new NP-211 project, and details will be presented in this paper.

MODEL DEVELOPMENT AT THE NSERL

WEPP erosion model technology development continues at the NSERL, and falls into three main categories, which are: 1.) Testing/enhancement of WEPP science model functionality; 2.) Enhancement/expansion of WEPP model interfaces and databases; and 3.) Creation of new combined models utilizing WEPP.

<u>Testing/enhancement of WEPP science model functionality</u>

Three areas are currently in progress or slated for work within the WEPP model. The first is the development of enhanced channel hydrology, to allow application of the model to catchments larger than the current recommended size (~260 ha). Forest Service model applications are often desired for larger areas to assess forest management and wildfire impacts on stream flow and sediment loadings. Cooperators at Washington State University (WSU) and the U.S. Forest Service in Moscow, Idaho have been developing new channel flow routines that either utilize numerical kinematic wave (Singh, 2001) or Muskingum-Cunge (Ponce and Chaganti, 1994) methods to simulate channel flow hydrographs (Wang et al., 2010). These have recently been incorporated within developmental versions of the WEPP code and Windows interface, and are undergoing further testing.

Tile drainage of the subsurface soil is an important agricultural management practice, particularly in the Midwestern U.S. Oztekin et al. (2004) independently tested WEPP and found at that time that the model was unable to match observed tile drainage field data. Since then, this portion of the WEPP code has been corrected for some coding errors, but has not been well tested. Cooperative work is planned between the NSERL and drainage faculty at the Ohio State University (OSU) to evaluate and improve the current WEPP tile drainage routines.

The third area of potential WEPP model improvement is in prediction of ephemeral gully development and soil detachment. Currently, WEPP utilizes ephemeral gully procedures and code that were originally developed for the CREAMS model. This requires that the model user knows a priori where the gullies will form on the landscape, as well as the gully dimensions (channel width, initial depth), slope, and cross sectional shape. Other fundamental process research in the NP-211 and NP-212 projects at the NSERL involve studying gully formation and subsurface hydrology effects through a combination of field observations and controlled laboratory experiments. As greater understanding and mathematical representations of the hydrology and detachment processes progress, we hope to utilize these to then enhance or completely replace the current WEPP approach.

<u>Enhancement/expansion of WEPP model interfaces and databases</u>

The current WEPP model can be utilized comprehensively through use of a Windows-based interface program, written in the C++ programming language (Flanagan et al., 1998). This interface is a stand-alone that can be downloaded from the WEPP web site (http://www.ars.usda.gov/Research/docs.htm?docid=10621), and installed on a personal computer, and it allows complete control over creation, editing, naming, and filing of model input files for climate, soils, slope, cropping/management, and watershed parameters. Simulations can be set up for a single hillslope profile, a table of multiple hillslope runs, or simple watersheds consisting of hillslopes, channels, and impoundments. One current limitation of the existing Windows interface (as well as all of the other model interfaces) is the number of available default cropping/management input files. There are currently less than 100 default example files, which are very helpful as a starting point for researchers applying WEPP, but are woefully lacking for field users trying to run the model with defaults at their locations. We are currently developing an expanded set of WEPP inputs for cropping/management that are based upon common systems present in each state that were provided to us by NRCS regional or state agronomists. These input files are being tested against similar RUSLE cropping/management sequences, and operation dates and plant parameters adjusted to produce similar plant growth and crop yields. With a minimum of 20 new crop files per state, we expect to have over 1000 new default files available within the next year.

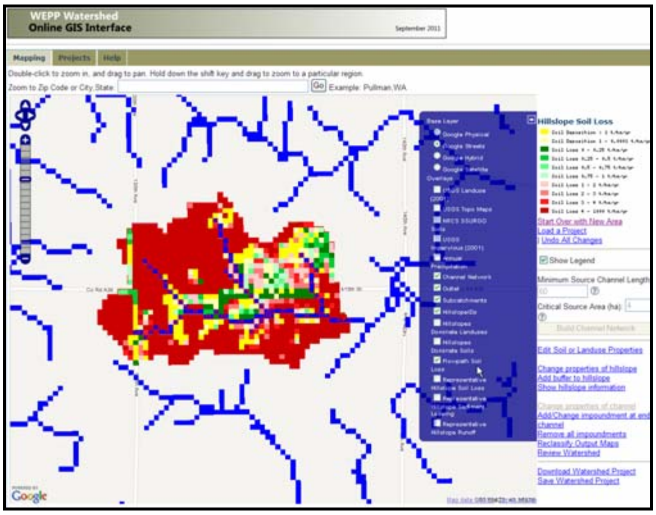

Figure 1. Screen shot of the WEPP web-based GIS interface with a small agricultural watershed in north central Iowa delineated, and spatial soil loss shown by grid cells. Red color indicates greatest soil loss, green indicates tolerable soil loss, and yellow is deposition.

An area of very active WEPP work is in development of internet-based Geographic Information Systems (GIS) interfaces. An initial prototype of this system was described by Flanagan et al. (2004), with the most recent versions utilizing the OpenLayers and MapServer GIS software and base images from Google Maps (Frankenberger et al., 2011; Flanagan et al., 2011). A screen shot from the newest WEPP web GIS interface is shown in Figure 1. We plan to expand the functionality of this interface to allow easier application to cropland and forest watersheds, and also provide a user with the ability to upload their own input data to our servers, to provide for better simulations than relying upon only default databases.

Creation of new combined models utilizing WEPP

Continuing work is underway on creation of a combined wind and water erosion model (WWEM), utilizing the water erosion components of WEPP and the wind erosion code from the Wind Erosion Prediction System (WEPS) developed by the ARS Engineering and Wind Erosion Research Unit (EWERU) in Manhattan, Kansas (Hagen, 1991; Hagen, 2004). Two prototype models have been developed, the first utilizing separate code components extracted from WEPP and WEPS and incorporated into the Object Modeling System (OMS) to create a new combined model. The second prototype is the current version of the WEPS model, in which the WEPP hydrology and water erosion routines have been incorporated. During testing of this WEPS version over the past 2 years, problems in runoff predictions compared to validation data were found, so currently further testing and revision of this code is underway. Testing so far has revealed corrections/changes needed in the infiltration and winter hydrology components.

Newly proposed in the recently revised NP-211 NSERL project is the creation of a WEPP-Water Quality model (WEPP-WQ), as well as a WEPP-CO2 version. The WEPP-WQ model would incorporate existing code from GLEAMS and SWAT, to allow prediction of soluble and sediment-bound nutrient and pesticide losses from fields and small watersheds. The WEPP-CO2 version would incorporate previously developed code that modifies predicted plant growth as affected by atmospheric carbon dioxide concentrations, so that global change studies can be conducted to examine the impacts of projected climate change on potential runoff and erosion, and effectiveness of conservation practices.

MODEL APPLICATIONS AT THE NSERL

A considerable number of modeling studies have been conducted recently at the NSERL and Purdue University, using several different natural resource models. These include the Annualized Agricultural Non-Point Source (AnnAGNPS, Binger et al., 2011) model, the Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998; Srinivasan and Arnold, 1994, Neitsch et al., 2011), and the WEPP (Flanagan and Nearing, 1995; Flanagan et al., 2001) model.

Herbicide transport and loss, particularly the herbicide atrazine, has been an important concern in the agricultural production regions of the United States. Atrazine is a relatively soluble compound and is frequently detected in municipal drinking water systems that obtain their source water from surface streams and rivers. Vasquez-Amabile et al. (2006) simulated flow and atrazine losses in the St. Joseph River (SJR) watershed (2800 km^2) in northeastern Indiana using SWAT, and found that the model was able to be satisfactorily applied to estimate atrazine losses and perform risk analyses. Larose et al. (2007) applied SWAT to the Cedar Creek watershed (CCW, 707 km^2) of the SJR, and found that after calibration the model performed well at estimating stream flow and atrazine concentrations in this catchment.

Heathman et al. (2008) applied both SWAT and AnnAGNPS to the SJR in uncalibrated modes to compare predictions of flow and atrazine transport. They found that in general both SWAT and AnnAGNPS could capture the trends in the observed flow data, but that AnnAGNPS significantly overpredicted the mean monthly streamflow. SWAT predictions of flow were not significantly different from the observed, and model efficiency was much greater than AnnAGNPS. Neither SWAT nor AnnAGNPS could satisfactorily predict atrazine concentrations in the water when applied in an uncalibrated mode. AnnAGNPS greatly underpredicted atrazine concentrations (1/100) in the water.

Zuercher et al. (2011) applied the AnnAGNPS model to the CCW of the SJR, as well as to the Matson Ditch subcatchment there, and utilized more detailed monitored data collected by the NSERL. They found that the model could be satisfactorily calibrated and validated to predict stream flow in these watersheds. Additionally, they identified and corrected an error in the AnnAGNPS pesticide routines that had been responsible for the underpredictions in the Heathman et al. (2008) study. Following correction of this coding error, the model was able to be satisfactorily applied to estimate pesticide concentrations.

Larose et al. (2011) again applied SWAT to the CCW to determine total phosphorus (TP) losses, as well as the impact of conservation buffers and land management changes. They found that they could successfully apply the model to simulate observed streamflow, but that it could not be successfully validated for TP losses. Application of buffers resulted in large reductions in predicted TP losses, while conversion of all land areas to grassland had no effect.

The WEPP model has also been applied to two small field watersheds (~2 ha) within the CCW, to compare model predictions of runoff and soil loss to field measured values (Cechova et al., 2010). Runoff could be successfully calibrated on one of the fields, but not on the other. Sediment losses could be successfully calibrated on both fields, but only validated on one. Problems encountered in this study included lack of a sufficiently large number of measured events. WEPP was also applied to a large subwatershed within the CCW (BME – 255 ha) in this same study, to evaluate the impacts of different conservation practices and land use. They found that conversion of all existing agricultural land to no-till practices would reduce predicted sediment loss by 48%, while conversion of all cropland to forests would reduce sediment loss by 96%.

Other modeling applications involve the use of data assimilation techniques to incorporate remotely-sensed as well as field soil moisture measurements from the NSERL field sites in the CCW to update model predictions. Han et al. (2011) incorporated surface soil moisture data assimilation with the Root Zone Water Quality Model (RZWQM) and SWAT model predictions. They found that daily or bi-daily assimilation of surface soil moisture improved the model predictions of soil moisture in the upper soil layers only. Additional efforts at the NSERL and Purdue University are applying data assimilation techniques with the SWAT model.

Future modeling applications will involve the WEPP, WEPP-WQ, WEPP-CO2, SWAT, and APEX models. APEX (Agricultural Policy EXtender, Williams and Izaurralde, 2006; Williams et al., 2008) is a field and small watershed scale model utilized by NRCS and ARS for the USDA Conservation Effects Assessment Project (CEAP) in combination with SWAT. We plan to apply APEX to our SJR watersheds as well as to a number of Mississippi River Basin Initiative (MRBI) watersheds in Indiana. Outputs from Global Environmental Models (GEM) for projected changes in atmospheric carbon dioxide content, precipitation, and temperatures will be downscaled from the large GEM grid size to scales appropriate for WEPP-CO2 model applications. Climate files for WEPP will be modified to account for the projected changes, and simulations conducted to determine the possible effects of the projected changes on runoff, soil loss, and sediment yields. When the WEPP-WQ model becomes available it will be combined with the WEPP-CO2 code so that the impacts on agricultural chemical losses can also be examined.

SUMMARY

The NSERL has a long history of development and application of natural resource models. Current work is heavily focused on models to better predict soil erosion, sediment loss, and agricultural chemical losses from fields and watersheds. During the next five years, substantial model development is planned, particularly with the WEPP model, as well as with data assimilation techniques with SWAT and other models. Model applications of SWAT, APEX, WEPP, and new WWEM, WEPP-WQ, and WEPP-CO2 models will also be conducted.

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