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Development of a Hillslope Erosion Module for the Object Modeling System

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Abstract. *A recent high priority need item of the USDA – Natural Resources Conservation Service (NRCS) was development by the USDA - Agricultural Research Service (ARS) of a combined water and wind process erosion model. This new model would ultimately replace individual erosion prediction software tools (e.g. RUSLE, WEPS, WEPP, etc.), and would provide consistent results in estimating soil moisture, runoff, plant biomass development, and residue cover, decomposition and burial by tillage. The new tool would take the best science available from existing models, and when necessary or appropriate new scientific relationships would be utilized. As a possible platform for development of the combined erosion model, the Object Modeling System (OMS) currently being developed by USDA-ARS GPSRU and Colorado State University in Fort Collins, CO was utilized. This presentation describes the process of creating a stand-alone hillslope erosion program (originally based upon the Water Erosion Prediction Project (WEPP) model code), testing of that program, then incorporation of the stand-alone erosion program within the OMS system. Evaluation of the new modular component, and work on creation of additional components and a complete functional erosion model within OMS will also be discussed.*

Keywords. Soil erosion, erosion prediction, OMS, modularity

Introduction

Soil erosion is a continuing long-term problem, threatening the soil, air and water resources of this nation and the world. Assessment of the likely occurrence of soil erosion caused by water or by wind, erosion rates, and impacts - both on-site and off-site, is becoming increasingly more important. Monitoring of soil erosion and sediment losses in the field is expensive, time-consuming and impractical for widespread assessments, thus computer simulation models have been developed for this purpose. Over the past 20 years, a variety of software tools have been created to assess soil erosion by wind or water.

The United States Department of Agriculture (USDA) – Agricultural Research Service (ARS) has been a leader in development of soil erosion and natural resource models. These include the Universal Soil Loss Equation (USLE, Wischmeier and Smith, 1978), the Revised Universal Soil Loss Equation (RUSLE, Renard et al., 1997), the Wind Erosion Equation (WEQ, Woodruff and Siddoway, 1965), the Revised Wind Erosion Equation (RWEQ, Fryrear et al., 1998), the Wind Erosion Prediction System (WEPS, Hagen et al., 1996), and the Water Erosion Prediction Project model (WEPP, Flanagan and Nearing, 1995).

For many years, the various erosion modeling efforts worked independently on their individual scientific components, user interfaces and databases. This led to duplication of effort, wasted resources, and multiple products requiring substantial maintenance and training support. ARS's main federal user agency, the USDA Natural Resources Conservation Service (NRCS) expressed its desire for a single user interface with a common database that could be used to run multiple soil erosion prediction models.

During 1996-2000, the RUSLE, RWEQ, WEPS and WEPP modeling teams worked together on a mutual project called MOSES (MOdular Soil Erosion System) with the goal of creating a common interface and database to conduct simulations with any of the 4 models (Meyer et al., 2001). Many meetings and screen design sessions occurred, and in late 2000, the first prototype MOSES-1 software was released that was based on the RUSLE-2 water erosion model and interface combined with the WEPS wind erosion model.

Evaluation of the MOSES-1 product by the MOSES team members and others indicated that the RUSLE-2 architecture would not be sufficient for the necessary common model interface. However, lack of administrative leadership and loss of interest by the individual projects after 2000 resulted in the end of the MOSES effort without a final product.

Since 2001, the various erosion prediction software projects have basically continued on their own individual development paths. The RWEQ effort ended, with no new development and minimal model support. RUSLE-2 continued development of their stand-alone custom C++ Windows model and interface, with the additional creation of an extensive database through cooperative efforts with the NRCS. WEPS continued development of their Fortran science model and stand-alone Windows interface, programmed in Java. WEPP completed work on stand-alone Windows interfaces, and progressed to GIS extensions (GeoWEPP) and web-based interfaces for both hillslope and watershed simulations (with web GIS tools, Flanagan et al., 2004).

RUSLE-2 has been implemented by NRCS in their field offices, and WEPS-1.0 was released in 2005 and is expected to also be implemented by NRCS sometime in the next year. WEPP is being applied extensively by the USDA-Forest Service (FS) and USDI-Bureau of Land Management (BLM), as well as by a large number of other public and private users.

In early 2004, the NRCS re-evaluated its need for erosion prediction technology from ARS. In the short-term, their most critical need from ARS was delivery of the WEPS model so that NRCS could conduct testing on it and subsequently implement it in their field offices as a replacement for the WEQ. The major long-term need of NRCS from ARS was stated as “For the long term, NRCS proposes to collaborate with ARS to build a single process based model to make erosion prediction calculations. NRCS proposes that this model be capable of making rainfall induced rill and interrill erosion computations, as well as computations for wind erosion together or independently of one another. This model would naturally incorporate the technologies currently in WEPS, the Water Erosion Prediction Project (WEPP), and those found in the Water Erosion Prediction Project - Simulation of Production and Utilization of Rangelands (WEPP-SPUR). Unlike the current models, the model proposed by NRCS would operate as a single decision support tool, and use common databases” (Letter from L.E. Clark, NRCS Deputy Chief, dated March 1, 2004).

The expressed need by NRCS subsequently led to a redirection of the erosion prediction research program at the USDA-ARS National Soil Erosion Research Laboratory (NSERL) in West Lafayette, Indiana. Administratively, a decision was made to stop any new development work on existing WEPP model science and interface code, and minimize resources towards support of the current WEPP software and existing users. The majority of the project’s resources were to be focused on development of a new combined water and wind erosion process model, to meet NRCS needs.

Top priority in the short term was to incorporate the existing WEPP hillslope erosion science code within the Object Modeling System (OMS) being developed by the ARS Great Plains Systems Research Unit (GPSRU) in Fort Collins, Colorado. The feasibility of using OMS as the platform for the full combined wind and water erosion model was also to be evaluated, along with creation of a full project plan for developing the new combined model. In the long term, the objective of the redirected project was to develop a fully functional continuous simulation wind and water erosion model for field application by 2011.

OMS (David et al., 2002, Ahuja et al., 2002) provides a modular modeling framework that allows implementation of single- or multi-process modules which can be compiled and applied as custom-tailored model assemblies. It was initiated in 1996 at the Friedrich Schiller University of Jena, Germany, then in October 2000 evolved into an interagency project between the ARS, NRCS and USGS (United States Geological Survey) in Fort Collins, Colorado. In 2005, the OMS programming team completed the development of most of the core components of the system, including:

1. A module-building component that facilitates the integration of existing (legacy Fortran, C, Java, etc.) code into the framework.
2. A repository containing modules that can be used to assemble a working model.
3. A model builder that assembles modules from the module repository into executable models and verifies data connectivity, compatibility in scale, and comprehensiveness.
4. A dictionary framework that manages model data type information and provides extended

semantics checking for module connectivity verification.

5. An extensible user interface that assists system users in model development and application.

Some major advantages of OMS are that it is all open source code written in Java, and it uses the component modules to break models into the smallest building blocks desired or necessary. Please also see the companion article to this paper (Ascough et al., 2005) for more detailed information on OMS and its application to soil erosion modeling.

Approach

As previously stated, the highest priority short-term goal was to develop a hillslope erosion module within OMS. This would provide both a starting point and learning exercise for application of OMS to a natural resource model, as well as create a useable module for interrill and rill erosion calculations that could be utilized for the ultimate common wind and water model, as well as by other models within OMS (e.g. RZWQM – Root Zone Water Quality Model).

The initial approach followed consisted of 3 steps. The first step was to isolate and convert the hillslope erosion portions of the existing WEPP v2004.7 model code into a running stand-alone Fortran program, in a format specifically conducive to subsequent inclusion with OMS. The desired format removed all common blocks, and placed all necessary variables into the main and subroutine argument lists. The second step in the process was to test and verify the stand-alone Fortran erosion program, and compare its output results to those from the full WEPP v2004.7 model. The third step was to incorporate the stand-alone model code within the OMS system and create a model that would reproduce the same results as the stand-alone Fortran program, given the same inputs.

Following successful creation of a model within OMS for hillslope erosion calculations, subsequent work could involve addition of more components (hydrology, water balance, etc.), expansion to include temporal looping (multiple days with/without storm events), and spatial looping (multiple spatial planes down a hillslope).

Progress in 2004-2005

September-October 2004

Work on development of a hillslope water erosion component began in September 2004. Initial efforts at that time focused simply on creation of a stand-alone Fortran model that duplicated the WEPP v2004.7 model erosion calculations. Largely this involved extracting the sediment detachment and routing routines (main subroutine ROUTE.FOR and subroutines for detachment, sediment deposition and enrichment under it), as well as associated code needed to read necessary inputs, compute variables needed in the erosion calculations, and write output. The erosion science embedded in these routines is discussed in depth in Foster et al. (1995), Finkner et al. (1989), Flanagan et al. (2001) and Flanagan and Nearing (2000).

A new MAIN program was needed, to direct the calls to the input, parameterization, sediment routing, and output subroutines. A large portion of the effort involved removal of all common blocks in the new code, and moving only necessary variables into the subroutine argument lists. An input file was created that contained only information necessary to drive the erosion calculations. This included hydrologic values of runoff depth, peak runoff rate, effective runoff duration, effective rainfall intensity, and effective rainfall duration. Other input variables included adjusted interrill and rill erodibilities and critical shear stress, soil texture information, and detached sediment particle information, surface roughness and friction factor values, and profile slope gradient data.

The initial stand-alone program was for simulation of a single flow element for a runoff event. A number of input files were created with a range of slope lengths, gradients, and shapes, and then the new program was run with these inputs and the outputs compared to a WEPP model simulation run with the same inputs. Values of some input variables to the stand-alone (e.g. effective rainfall duration) had to be obtained by modifying the WEPP v2004.7 code to write out these internal model values.

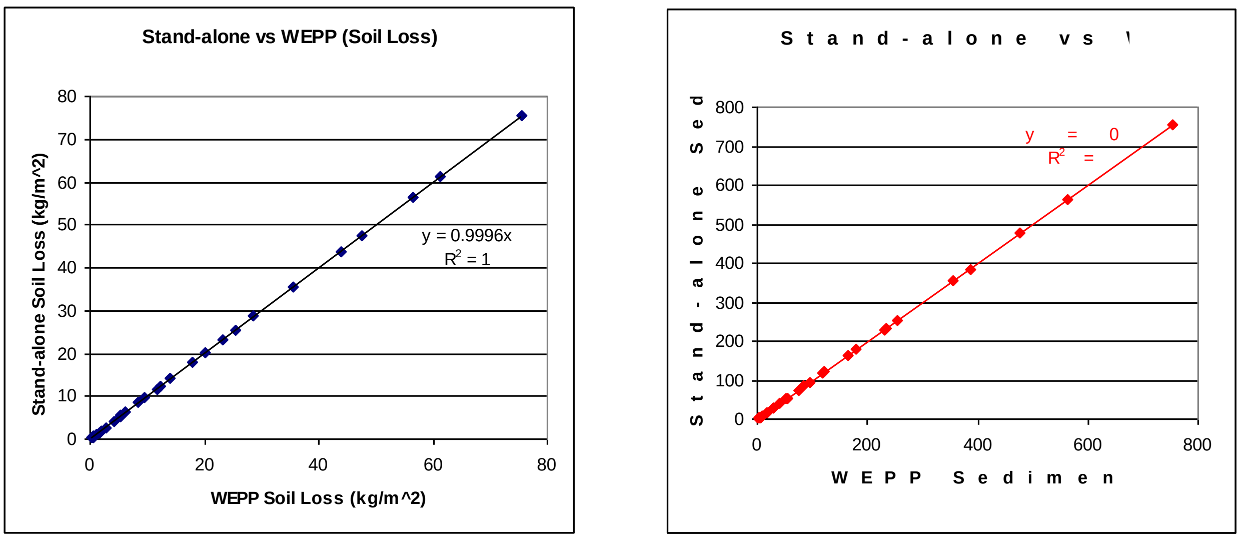


Figure 1. Comparison of soil loss and sediment yield results for initial erosion stand-alone program and original WEPP v2004.7 model.

This testing resulted in a number of corrections being made to the stand-alone code, and ultimately a verified single runoff event program that operated correctly for a single spatial plane. Figure 1 shows the results of the final test comparisons between the stand-alone and the original WEPP v2004.7 model.

January-February 2005

During early 2005, the code within the stand-alone was made active to handle multiple spatial planes. The number of planes was added as an additional input in the input files, and then data was added to new input files for multiple planes. The enhanced stand-alone program was tested for a range of inputs – for 1, 2, 4, and 10 overland flow planes and compared to WEPP v2004.7 simulation outputs. For some of the stand-alone inputs, variable values internal to the WEPP code had to be output, and then entered into the stand-alone input files.

This effort resulted in several corrections to the stand-alone code, and ultimately a verified single event program the operated correctly for multiple spatial planes. The spatial looping in this version of the stand-alone functioned very similarly to that in the original WEPP program. Figure 2 shows the MAIN and 30 subroutines in the erosion stand-alone program. This program reads from a single input file and creates two output files that are almost identical to current WEPP model outputs.

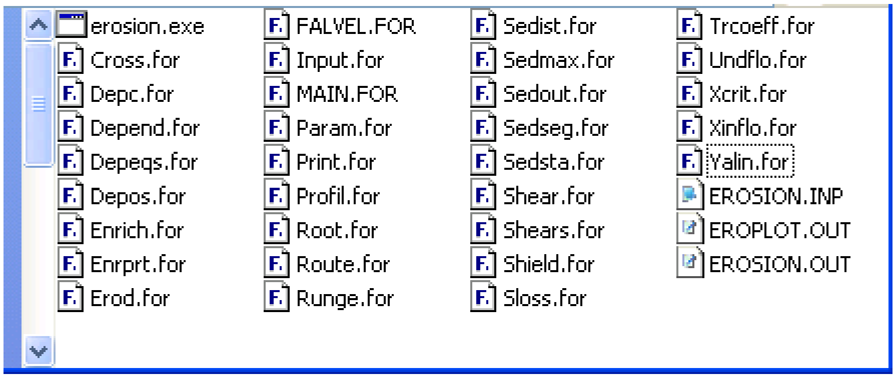


Figure 2. Listing of stand-alone Fortran erosion program subroutines, I/O files, and executable from February 2005.

March-April 2005

The current WEPP model simulates a hillslope as a set of linked overland flow elements, each of which can have different soil, cropping management, water balance, etc. The internal model structure of WEPP and of the February 2005 erosion stand-alone did spatial looping within the MAIN program code or various subroutines. While this approach works adequately for the WEPP model, it is potentially not the best approach for a modular erosion component that may be used within a variety of other models (including a common wind and water model) that may have or require different spatial representations.

A decision was made at this time to remove all of the spatial looping and arrays within the existing stand-alone code, then to have the necessary spatial (and temporal) looping be handled by the OMS system itself.

Additionally, an existing stand-alone hydrology program that had earlier been created by J.C. Ascough based upon the WEPP hillslope infiltration and overland flow routing (Stone et al., 1995) was modified for incorporation into OMS (removal of common blocks, variables in argument lists, etc.). This code included both the Green-Ampt-Mein-Larson (Mein and Larson, 1973) computations for infiltration during an unsteady rainfall event (Chu, 1978) needed to predict runoff depth, as well as the kinematic wave solution using the method of characteristics to provide the storm runoff hydrograph and peak runoff rate needed in the erosion model (Stone et al., 1995).

The hydrology stand-alone was also modified to produce both standard WEPP-type hydrology outputs as well as a pass file for the erosion stand-alone, which contained the runoff depth, peak runoff rate, effective runoff duration, effective rainfall intensity and effective rainfall duration. Subsequently, those 5 inputs were removed from the erosion stand-alone input file, and the program modified to instead open and read from the hydrology pass file.

Following additional testing and code corrections, the work this month resulted in a set of independent stand-alone hydrology and erosion programs that could communicate (through a pass file) with each other, and were in a format ready for incorporation within OMS.

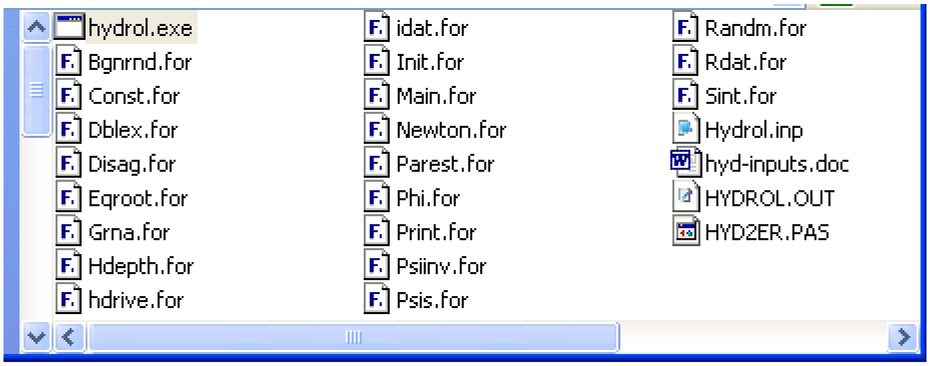


Figure 3. Listing of stand-alone Fortran hydrology program subroutines, I/O files, and executable from April 2005.

Figure 3 shows the new stand-alone hydrology code listing, including the MAIN program and 19 subroutines. This program reads data from a single input file, and writes two output files – one with storm hydrology output identical to that from WEPP, and the other a hydrology-to-erosion pass file

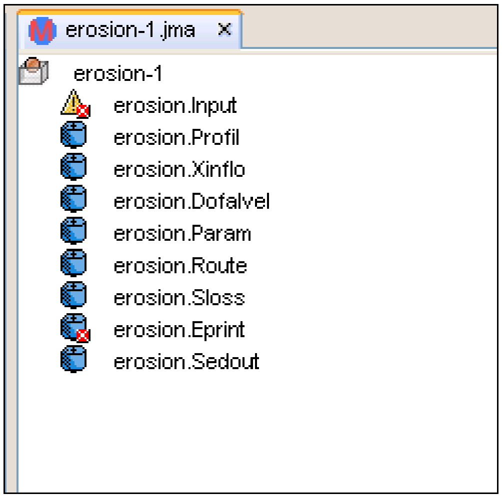
June 2005

Work during June 2005 was almost entirely on utilizing the new OMS version 1.1.1 to create erosion and hydrology modules and models. Initially, the major subroutines in the stand-alone Fortran erosion program that were called from the MAIN were converted within the OMS system to component modules. During this process, OMS supplied an automatic Java “wrapper” generation, which allowed the Fortran code to be embedded into the modeling system at the function level.

Once all component modules had been created and the entire project “jarred” (which compiles all of the Fortran and Java code into executable objects and puts it all into a “jar”), an erosion model was created in OMS, using the modules. We learned that additional modifications to the Fortran code and modules were required, as some logic that was present in the stand-alone MAIN program had to be removed and either placed in existing modules, or new modules had to be created. Ultimately, an erosion model was created within OMS that duplicated the functionality of the stand-alone and produced identical outputs.

Once the erosion model had been completed, a similar procedure was followed to create a hydrology model within OMS that duplicated the functionality of the stand-alone and also produced identical outputs. The structure of both of these initial independent erosion and hydrology OMS models is shown in Figure 4.

The two independent models could be run in sequence, first the hydrology, which read rain storm intensity inputs and other hydrology inputs and produced an output hydrology pass file, and then next the erosion, which read the pass file along with other inputs and conducted the hillslope interrill and rill erosion computations. The next step was then to create a single model composed of all of the hydrology and erosion components for a single event and flow plane, first transferring information between the two via the pass file, and then removing the need for the pass file by instead exposing the 5 variables there to the OMS system in some of the hydrology and erosion component argument lists. This turned out to be a very simple task, and the combined model produced output identical to the separate models running in sequence.



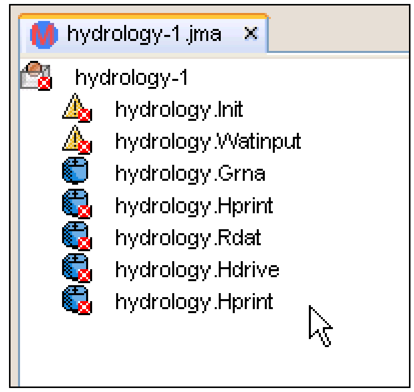


Figure 4. Initial erosion and hydrology models in OMS, showing the component modules used. These were for a single event and single flow plane.

The remaining task was the most difficult and challenging – creating a linked hydrology and erosion model that properly handled spatial (multiple linked flow planes) and temporal (multiple daily storm inputs). This required some considerable modifications to the existing code, as changes were required in where and how particular inputs were read. For example, the rain storm intensity inputs had to be separated from the rest of the hydrology inputs, and put into a separate "climate" file that just contains that information. Additionally, parameter (i.e. constant) values for both hydrology and erosion were placed into separate input files that are only read once at the beginning of the model execution. State (i.e. variable) values for both hydrology and erosion were also placed into separate input files that are read each day for each spatial plane.

Ultimately, a combined hydrology and erosion model that would simulate multiple spatial planes for multiple days was created (Figures 5 and 6). Figure 5 shows the entire OMS screen with the modeling projects open on the left, the model in the center, attributes and properties of the model on the right-hand side, and model output at the bottom. Debugging the hydrology/erosion model required addition of write statements of important internal variables to the screen.

Figure 6 shows a close-up of the hydrology/erosion model (named "erroder"), along with the control structures used. At the beginning of the program, some basic hydrology parameters are read from the input files, and output files are opened. An important input is the number of simulation days from the top of the climate input file. Then a conditional is used in the OMS logic to check whether to continue in the daily time loop, or if the number of days read in from the climate file has been exceeded – if so the program ends. If the number of days is less than the maximum, the program does daily initializations and reads in the rainfall intensity inputs from the climate file. Another conditional block is used to step through the spatial planes each day. Within the spatial loop, more initializations are done, and hydrology and erosion state variables are read in from input files. Then another conditional is used to only do the infiltration/runoff and soil loss calculations for a plane if there is rainfall on a day. If there is rainfall on a day, infiltration and runoff are computed for each spatial plane, and a final conditional block only allows erosion calculations if runoff or run-on occurs for a plane. When runoff and erosion are predicted to occur, information is written to output files for each spatial plane on each day.

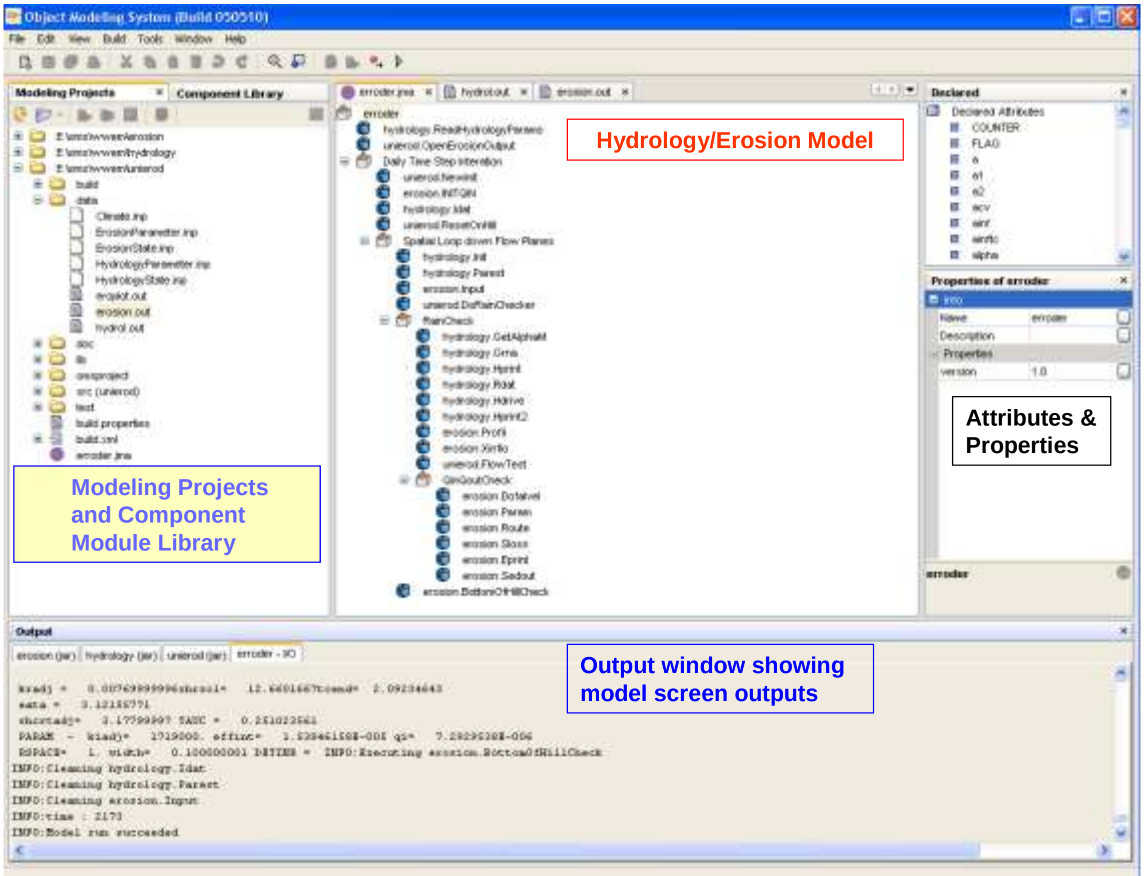


Figure 5. OMS screen showing combined hydrology/erosion modeling projects on left side, model in center, attributes and properties on right, and model screen output at bottom.

Output from the OMS hydrology/erosion model was compared to that from the stand-alone Fortran programs, run with the same input data. Ultimately, after repeated modifications and corrections to the OMS code, it was verified to produce the same outputs.

Further work on utilization of alternative OMS model logic other than conditionals, namely “entities” was also initiated at the very end of June. Entities will allow spatial information to be retained from day to day, so that information in the input files that only changes spatially but not temporally will only have to be read in one time (as opposed to being read in each day in the current model).

Efforts currently underway are to add more components, including daily water balance, plant growth, parameterization, and wind detachment to the system. The planned timeline is to produce a prototype hillslope continuous simulation water erosion model in OMS including water balance, plant growth and parameter updating by March 2006. By December 2006, a prototype single event wind and water model should also be available.

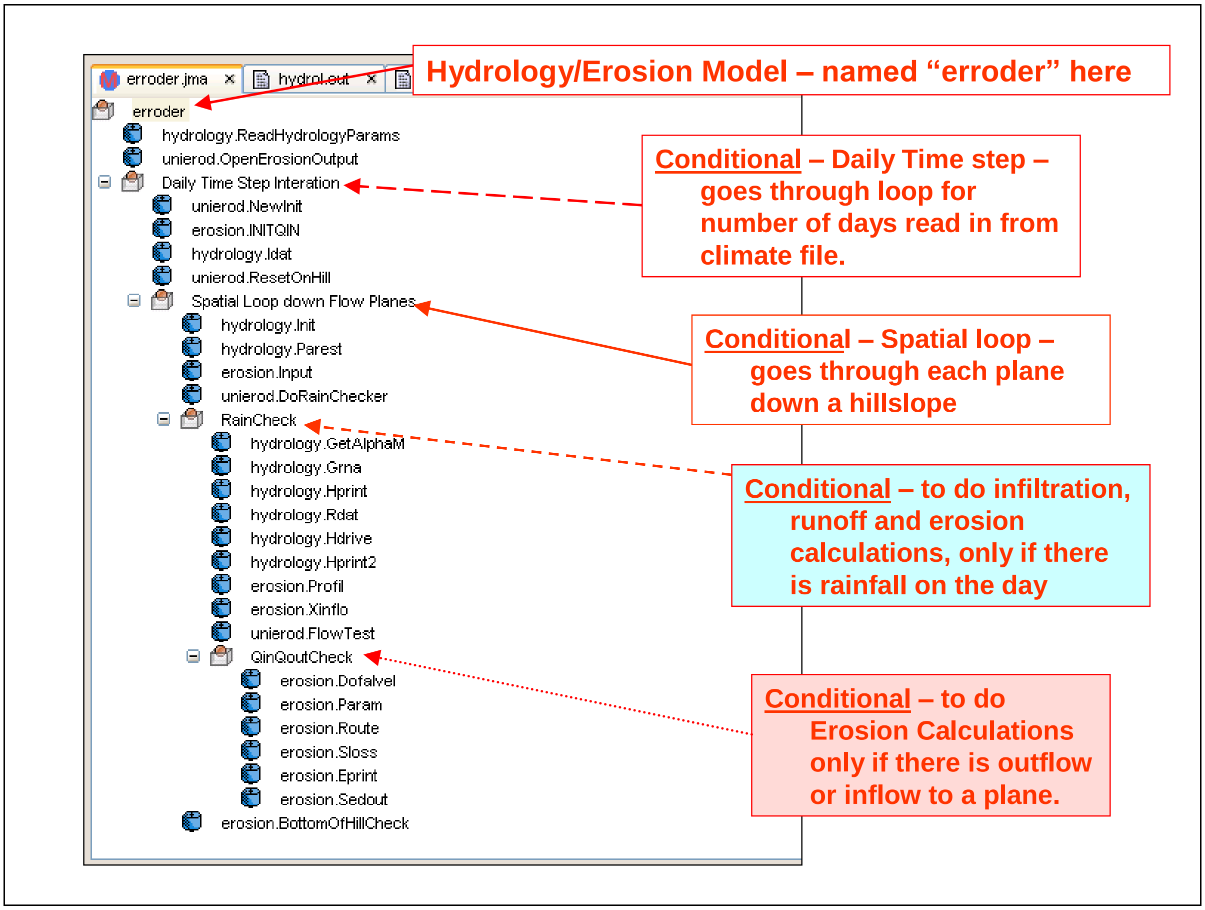


Figure 6. Combined hydrology and erosion model within OMS, with temporal and spatial looping, and conditionals which control whether runoff is calculated (only if there is rainfall) and if erosion is calculated (only if there is runoff or run-on to a plane).

Summary and Conclusions

Stand-alone water erosion Fortran programs were created based upon the full WEPP model code, and verified against the original WEPP code. The Object Modeling System was used to successfully create individual hydrology and water erosion models for a single storm, and then created a linked hydrology and erosion model for a single storm, that was verified against the stand-alone hydrology and erosion programs. Finally, an OMS model was successfully created that performed temporal (multiple storms) and spatial (multiple flow planes) simulations, and is currently being tested and revised.

More work is underway to add additional component modules, and expand the continuous simulation to include full water balance simulation on a daily basis for each flow plane. An enhanced plant growth module is being developed by scientists at GPSRU, and work will soon begin with cooperating ARS scientists at the Wind Erosion Research Unit (WERU) to develop a wind detachment module as well. This work is contributing to the ultimate development of a combined wind and water erosion process model for use by NRCS and other federal, state and local agencies.

OMS has been shown to be a useful tool for building component modules and models. Further enhancements to OMS will improve its usefulness to scientists and model developers.

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