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A user agency's view of hydrologic, soil erosion and water quality modelling

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Abstract

The Natural Resources Conservation Service (NRCS) of the US Department of Agriculture provides assistance for land management planning and the use of conservation measures on private farmland in the United States. The NRCS must concern itself with a broad range of issues with regard to models and their application to support the assessments and decision making associated with these activities. These issues include the basic science for the description of physical processes, user issues in the practical application of the model, and software maintenance. In recent years, a significant amount of effort has gone into implementing existing agricultural hydrology/erosion/water quality models. There are, however, some important areas of model development that need to be addressed, including: reconciling the strengths and weaknesses of existing models; accounting for spatial variability of precipitation over the catchment; rectifying weaknesses in the stochastic climate generators currently included in some erosion models; improving the representation of runoff generating processes and water flow paths; and improving our understanding of ephemeral gully (thalweg) erosion and including algorithms to describe it. New model development also needs to follow modern standards of software engineering to ensure code reusability and maintainability. Although the NRCS is primarily a model user agency, it must be involved in all aspects of model development as well as model application to ensure satisfactory results. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

The Natural Resources Conservation Service (NRCS, formerly Soil Conservation Service) is the agency of the US Department of Agriculture (USDA) whose main responsibility is providing technical assistance to farmers in the application of conservation measures for the reduction of soil erosion and for minimizing water quality degradation. It also assists on related issues, such as wetlands preservation, water management, flood control, and the general ecosystem health of farmland. To accomplish this mission, the NRCS has a network of nearly 3000 local field offices, which are supported by a hierarchy of state offices, regional offices, and several national centers and institutes. Erosion and water quality models are important tools used by NRCS for planning the application of conservation measures at the field, catchment, and river basin scales.

2. Current status of models in NRCS

In 1990, NRCS reviewed a number of models and decided that five erosion/water quality models developed by the research agency of USDA, the Agricultural Research Service (ARS), looked the most promising to meet the agency's needs: AGNPS, EPIC, GLEAMS, NLEAP, and SWRRB (Leonard et al., 1987; Young et al., 1989; Sharpley and Williams, 1990; Arnold et al., 1990; Follett et al., 1991, respectively). Of these, AGNPS and SWRRB are catchment scale models, and the remaining three are field scale models. A major effort was begun to implement these five models throughout NRCS. This included some demonstration projects, a training program on the use of the models, and the establishment of a network of technical experts throughout the country. In addition, a UNIX workstation-based user interface to the AGNPS and SWRRB models was developed, which streamlines access to key databases and facilitates the preparation of input data sets (Natural Resources Conservation Service, 1996). Another use being found for models is the development of reference materials, tools, and guidance for field offices, which themselves do not involve the use of a model, but which are developed by summarizing the results of numerous model runs. Examples of this are a pesticide screening tool, which is based on many runs of the GLEAMS model, and a tile drainage guide, which is based on DRAINMOD (Natural Resources Conservation Service, 1994) simulations.

In a related arena, the NRCS is expending considerable effort to implement the Revised Universal Soil Loss Equation (RUSLE; Renard et al., 1991) to replace the USLE in field offices. The WEPP model (Flanagan and Nearing, 1995; latest information available on the Internet at http://topsoil.nserl.perdue.edu/weppmain/wepp.html) has not yet been completely reviewed by NRCS and hence has not yet been officially implemented. Current thinking is that eventually WEPP will find use in state offices and selected field offices, but it is not expected that it will be routinely applied in all field offices, as perhaps originally thought. Instead, RUSLE will be relied upon for most ordinary evaluations at field offices.

Recently, the NRCS has taken a more active role in model development than it has in the past. This closer relationship with model developers began during the development of the WEPP model (starting in the mid-1980s). A formal organizational process by which model development and support can be achieved with greater coordination of effort between NRCS and ARS is now in place. An example of this new cooperation in model development is the project to enhance the existing event-based AGNPS model to create a continuous simulation version called AGNPS98 (latest information available on the Internet at http://www.sedlab.olemiss.edu/AGNPS98.html), which involves personnel from both NRCS and ARS equally in the development of the model.

3. Needed improvements in hydrologic and erosion process representation in models

The description of water fluxes over and through the soil is the foundation of an erosion model. Without an accurate representation of the paths the incoming precipitation takes once it hits the ground, the rest of the modelling exercise is questionable. Improvements in process representation are a key area in which model developers must focus significant effort.

3.1. Precipitation input

The first prerequisite for accurate hydrologic modelling is an accurate estimate of the precipitation. For the field and small catchment scale, it is not particularly difficult to do this, if one has a rain gauge in or near the area (although it is, of course, problematic if no such gauge exists, and one must estimate the precipitation from distant stations). At larger scales, however, the spatial variability of precipitation becomes important. It is no longer adequate to assume that precipitation is uniform over the entire area, particularly if orographic, convective, or other spatially variable influences are important. Textbook procedures, such as Thiessen polygons, do not adequately account for orographic influences and make highly simplistic assumptions about the spatial distribution of precipitation. Newer spatial interpolation techniques, such as PRISM (Daly et al., 1994; latest information available on the Internet at http://www.ocs.orst.edu/prism/prism_new.html) to map climatological average precipitation, or the model used for daily time series based on detrended kriging developed by Garen et al. (1994) and Garen (1995), can be used to obtain better estimates of spatial fields of precipitation. Sub-daily fields can be derived by disaggregating daily fields on the basis of high time resolution precipitation gauges in the vicinity, as was done by Garen and Marks (1996).

Improvements in stochastic weather generator models are also needed for those applications using this as the source for meteorological input data rather than historically observed data. Problems with existing generators have been documented (e.g., Favis-Mortlock, 1995; Johnson et al., 1996a). In the US, work is underway not only to improve the statistical behavior, but also to add other weather variables to the suite being generated and to increase the time resolution. An additional improvement is the development of a methodology of spatially interpolating model parameters that takes topographic variability into account (Johnson et al., 1996b). These developments are being made to a model called GEM (Johnson et al., 1996a,b), previously known as USCLIMATE (Hanson et al., 1994). Once incorporated into erosion models, these developments should improve the input, thereby enhancing predictive accuracy.

3.2. Water fluxes and runoff generating processes

Moving from the field scale to the catchment scale introduces a whole new set of processes that are important to consider to obtain an accurate depiction of water fluxes. These include the interrelated concepts of partial contributing area processes, terrain control of water flow paths, and subsurface flow. The advent of geographic information systems, digital terrain models, spatial data sets, and fast computers has enabled rapid progress in the ability to describe these processes and their spatial variability.

The incorporation of a more accurate and physically realistic representation of all of the various runoff generating processes into erosion models is an urgent model development need. Except for the WEPP model, the algorithm used by virtually all USDA models for the calculation of runoff is based on the Soil Conservation Service curve number technique (Soil Conservation Service, 1985). Because of its simplicity, relative ease of use, and availability of information for the estimation of the curve number, it has been used widely. The arguments for and against this model have been voiced for years; many of these issues were recently reviewed by Ponce and Hawkins (1996). It continues to be successfully used, however, to estimate streamflow volume for a rainfall event in the design of hydraulic structures, which was its original purpose. In this application, the flow path of the water through the catchment does not matter, so the model only attempts to predict the total flow for the event at the catchment outlet. It does not distinguish between infiltration excess overland flow, saturation excess overland flow, shallow subsurface flow, etc. As the method is applied in the current generation of agricultural erosion/water quality models, however, there are two stretches of the curve number method beyond its original purpose. One is its use in continuous simulation models for the calculation of runoff and soil moisture on a daily basis. The interpretation given for this usage is that each day’s precipitation is considered to be an independent ‘event’, but this still represents an extension of the method. The other stretch is that the ‘runoff’ calculated is assumed to be overland flow occurring over the entire grid cell, field, or catchment. This involves the definition of runoff as one specific process occurring on the land surface, whereas the meaning of runoff in the original development of the model was different (i.e., streamflow) and did not specify any particular runoff generating process.

One element for the improvement of the physical description of runoff generating processes is the use of infiltration models instead of the curve number. This has been done in some models, such as WEPP and KINEROS (Woolhiser et al., 1990). This would give a more precise representation of infiltration excess overland flow and would make it more straightforward to estimate the impacts of conservation measures, tillage, and other operations on soil texture and hydraulic properties.

One of the most important areas in which progress is being made centers around the topographic control and subsurface dynamics of water movement. Much has been learned in recent decades about these processes and their importance in runoff generation. The well-known TOPMODEL, introduced by Beven and Kirkby (1979), and used and enhanced by many workers since, is an example of a model that attempts to embody these principles to simulate the saturation excess overland flow mechanism. Although hydrologists have recognized the importance of these processes for the generation of streamflow, their importance in the realm of soil erosion is less widely recognized. It has been shown, however, that erosion from saturation excess overland flow in the winter during mild rains can be significant (Kwaad, 1991). It has also been shown that topographic convergence and subsurface processes are related to erosion due to the formation of ephemeral or thalweg gullies. Several studies (Moore et al., 1988; Baade et al., 1993; Baade, 1994; Huang and Laflen, 1996; Poesen et al., 1996) not only have shown this connection, but they also point out that this is an important mechanism of soil loss, which is not currently considered in most erosion models. This is an important area requiring further research, as existing models that describe ephemeral gully erosion (e.g., Thorne and Zevenbergen, 1990; Soil Conservation Service, 1992) are still in need of basic development and refinement.

Techniques involving geographic information systems and algorithms for digital terrain analysis (Quinn et al., 1991; Costa-Cabral and Burges, 1994; Garbrecht and Martz, 1996; Tarboton, 1997) are readily available and could greatly help improve the hydrologic process description in models. These algorithms can be used to identify catchment boundaries, determine stream networks, and establish overland flow paths. With this, spatially detailed information is available, making possible the development of either fully spatially distributed models, for example, the SHE model (Wicks and Bathurst, 1996), LISEM (De Roo et al., 1996), and the models of Fett (1993) and Wigmosta et al. (1994), or semi-distributed models, such as TOPMODEL (Beven and Kirkby, 1979) and the models described by Schumann and Funke (1996) and Schultz (1996). An early version of the topographic analysis package TOPAZ (Garbrecht and Campbell, 1995; Garbrecht and Martz, 1995) has been incorporated into the NRCS's AGNPS/SWRRB model interface, but only a portion of the full capabilities are actually used, as AGNPS and SWRRB are not structured to take full advantage of this information.

3.3. Significance of accurate process descriptions

One of the most significant outcomes of the next generation of erosion models will be more precise selection and siting of conservation measures in accordance with the hydrologic and erosional processes actually occurring (Zollweg et al., 1995). It could potentially make a great deal of difference in the measures applied whether the erosion source is diffuse or concentrated. With respect to water quality concerns, the runoff generating process and the flow path of the water could also make a great deal of difference in terms of the nutrient and pesticide loading to receiving waters. Spatially distributed models with improved descriptions of physical processes should be useful tools in planning and implementing more cost-effective conservation practices.

4. Model application issues

In the application of any model, there arise issues related to model choice, the applicability of a model in a given area, the interpretation of the results, and the ability of users to apply the model meaningfully.

4.1. Model choice and duplication among models

Choosing an appropriate model for the task at hand can be difficult and confusing, especially to the non-expert. Although some guidelines have been developed, this is true even with the five models selected for use by NRCS. This situation has arisen because most of the current models have been developed as more or less independent efforts by individual scientists or working groups. These models often contain components borrowed from one another, but then each has its own unique parts as well. The result, however, is that there is overlap in the capabilities of the models. A recent recognition of this fact within USDA has motivated the creation of a team to compare and evaluate the merits of the two catchment/river basin scale models adopted by NRCS, SWAT (Srinivasan and Arnold, 1994; formerly SWRRB) and AGNPS/AGNPS98. SWAT is based on a spatially lumped approach, where each spatial unit is a sub-catchment within the river basin, while AGNPS/AGNPS98 is grid-based. The variables predicted, however, are similar. It is hoped that through this model review, the advantages and disadvantages of each approach can be evaluated and that duplication of model development effort can be minimized.

From a user agency's point of view, it might be desirable for several reasons to consolidate these models into perhaps three, based on spatial scale. This is closely aligned with the original concept for the WEPP model, with a point or field scale model, a small catchment scale model, and a river basin scale model. In addition to erosion, however, it would be necessary for NRCS's purposes that these models also contain nutrient and pesticide simulation capability, for the complete assessment of agricultural water quality concerns. This consolidation would greatly simplify model choice and implementation and would reduce the training required, as there would be only one model officially sanctioned by the agency for any given spatial scale. It would certainly be undesirable if such consolidation stifled future model improvement and development, but with appropriate openness and a willingness on NRCS's part to continue working with model developers, this should be avoidable.

4.2. Regionalization and calibration

In research areas and other data-rich situations, all or most of the input data needed are available for the application of a model. In 'real-world' applications, however, some of these data may be lacking, and some method has to be found to estimate the required input data. Another 'real world' issue is that all models require calibration, and one must expect to do some parameter adjustment to ensure good results.

One concept for dealing with the missing data issue is to have a method of estimating model parameters from commonly available information, such as land use, soils, and other data on the physical characteristics of the area to be modelled. That is, methods for regionalizing parameters are very useful. This has been attempted for many hydrologic models; the SCS curve number, for example, is essentially a regionalized parameter (part of the reason for its popularity).

Sometimes, agricultural models are applied in areas where no streamflow or sediment data are available, therefore making calibration impossible. In these cases, it is important that models can be applied in data-poor areas and that reasonable results can be obtained without calibration. It must be clearly understood by the user, however, that calibration is virtually always necessary and that the simulation error is greater without calibration (e.g., Grunwald, 1997). Because model calibration can be a subjective process, leading to different parameter values depending on the user (e.g., Botterweg, 1995), it is important that models be developed with a consideration of calibration needs, that is, providing a convenient method for doing so and minimizing the number of calibration parameters to a manageable number.

Some of these issues can be better dealt with if the model developer and model user work very closely together to define the constraints and requirements for the model. In this way, these model application realities are explicitly considered in the model structure so that the user is not presented with a model that is too difficult or too impractical to apply.

4.3. Interpretation of results

One of the topics of discussion among erosion modellers is whether models can be relied upon to give reasonably accurate predictions of absolute amounts of erosion or whether they can only give appropriate relative predictions. If the latter is true, then a model can only be expected to give a relative ranking of the effects of alternative land management and erosion control measures—which one is best, next best, and so on. Some might extend this to say that the relative magnitudes of erosion among the alternatives can also be represented—e.g., Alternative A causes twice as much erosion as Alternative B, etc. Whether a model can be expected to give accurate enough predictions to say that Alternative A will result in x t/ha per year, and Alternative B will cause y t/ha per year is less certain.

This uncertainty must be borne in mind when interpreting any modelling results and especially when basing decisions on them. It is all too tempting to imply greater accuracy than is warranted. In fact, it is often unavoidable, because many decisions about the selection and implementation of land management or erosion control practices require cost-benefit considerations, which necessarily require quantitative absolute predictions of erosion for each alternative. Likewise, the determination of whether proposed conservation practices will bring erosion below the specified tolerance also assumes that the model gives reliable estimates of the absolute amount of erosion.

Despite the scientific caution on the part of modellers, even though it is well-warranted, it is inevitable that model users and decision makers will make these quantitative interpretations of model results. Scientists and model developers need to continue to voice the necessary caveats associated with their models, as the clear communication of model weaknesses and limitations, as well as their strengths, is still vital. Model users and decision makers, on the other hand, must be prepared and willing to understand these issues and exercise the appropriate caution when making conclusions based on model results. It is essential, therefore, for both groups to attempt to understand the other, to recognize each other's needs and philosophical tendencies. An agency like NRCS must play a bridging role between these two camps and foster this mutual communication and understanding, so that models are meaningfully applied.

4.4. User issues

NRCS faces a number of issues that relate to the model user, such as a model's ease of use, data availability, expertise of the user, and training.

Process simulation models are by their very nature complex, and it is not easy to make them simple to use. The NRCS's graphical user interface to the AGNPS and SWRRB models or the interface to the WEPP model attempt to address this. By accessing major data bases, making data input easy, and providing graphical output viewing tools, the laborious task of input data preparation is simplified, and the mechanics of operating the models are streamlined. While these interfaces are an important step forward in facilitating the implementation of models in the field, one should not be seduced by their apparent ease of use that these models can be meaningfully applied by novices or non-experts. There remain many pitfalls and limitations, and there are many areas requiring knowledge of hydrology, erosion, and the algorithms used in the model. It should not be expected, then, that anyone should be able to sit down at the computer, push a few buttons, and arrive at a meaningfully applied model. The purpose of the convenient interface, then, should be viewed not as a substitute for expertise, but as a way to minimize tedious mechanical tasks and to free the investigator to concentrate on the essential issues at hand.

Another issue has been the recognition that model training and user support has shown itself to require a very large effort. The implementation of any model agency-wide must therefore be very carefully planned, with full recognition that training and support will require a major commitment of resources. This is part of the motivation for the earlier suggestion of consolidating models; this would reduce the training and support required as well as simplify model choice. Because of this large training and infrastructure required, the danger exists to become entrenched in a particular model or version thereof. The implementation of models must be flexible enough to be able to embrace new versions or new models without enormous expenditures of resources in re-training or re-engineering supporting software.

5. Software development and support

As the number of models developed has increased, it has become evident that a major expenditure of time and effort is required to develop, maintain, enhance, and support the software. In other words, the USDA has discovered it is in the software business. This requires a managed process to address issues such as coding standards, bug fixes, version control, documentation, and long-term continuance of the model (even after the retirement of key personnel). Since these require significant resources, it is important to address these needs in a formal and planned manner.

In the past, and perhaps still to a large extent, models have been written primarily by scientists and not by professional programmers and software engineers. Although useful models have been produced, modern programming techniques could be used to great advantage to improve the software-related aspects of models and make these issues more manageable. Considerations in this regard include code reusability, code modularity, and object oriented model design.

In the current suite of models used by NRCS, there is a considerable amount of duplication of science and program code. Some of this has occurred as code was 'borrowed' from one model and used in a new model. Often, considerable model development time has been spent rewriting and modifying this code so that it would fit into the new model's structure. One solution used in the software industry to minimize this expenditure of time is object oriented programming. With this technique, the idea is to build a model as much as possible from well-defined components (objects), each of which is contained in its own source file or in a library of objects. An object encapsulates as much information as possible about the model component, thereby maximizing the reusability of the object without reprogramming and making the object easy to include in the model. Perhaps the most well-known object oriented programming language is C++, for which there are many textbooks available. Unfortunately, most existing models are written in FORTRAN, which has robust mathematical capabilities but is not an object oriented language. In addition, most scientists have not been trained in object oriented languages, therefore they are reluctant to adopt such an approach, and it would be a difficult paradigm shift.

Modularity of code is an in-between concept that can at least help make code more portable and reusable. For modular code to be reusable, strict adherence to a programming standard by model developers would have to be enforced. This is done, for example, in the well-known Modular Modeling System, developed by the US Geological Survey (Leavesley et al., 1996). In this system, modules can be written in standard languages, such as FORTRAN or C, but they must adhere to strict input and output data specifications. All modules written to meet these standards can easily be reused in developing other models within the system. Adopting an object oriented language, however, would by definition enforce a programming standard and make code more reusable.

With the explosion of the Internet and the potential for every model customer to be connected to the World Wide Web, it would be desirable to deliver modelling technology over the Internet. The difficulty is that there is a multitude of platforms connected to the Internet, and making model versions available so that they can be run on all of these platforms would be a maintenance nightmare. A solution to this may be available through the use of the new programming language called Java. This language is being incorporated into Web browsers, such that programs written in Java can be interpreted and executed by the browser. To speed up execution, a Java compiler, called Just in Time, is being developed by software companies. This would work with the Web browser and Java code to create an executable program for the user's specific computer. The software industry is developing these capabilities because they want to minimize resources required to develop and maintain code while at the same time making their applications available to the broadest market possible. While the applicability of these concepts for large simulation models is at present still unknown, model development and maintenance objectives in NRCS may benefit from these happenings in the software industry.

6. Conclusion

Many new opportunities lie before the NRCS in the related areas of hydrology, erosion and water quality modelling. New emphasis on being actively involved in model development has already shown itself in several modelling projects, such as AGNPS98 and the continued development of the GEM model. NRCS is also helping to identify and promote further research, such as improving the representation of runoff generating processes and ephemeral gully erosion in models. NRCS must look into ways to promote the practical application of models by simplifying model choice and by providing training and guidance in appropriate model use and interpretation of the results. It must also consider modern techniques of software engineering to make model development and maintenance more efficient. All of these efforts point the way toward improved simulation capabilities for the support of agricultural land management and decision making.

7. List of acronyms

AGNPS	AGricultural Non-Point Source pollution model
AGNPS98	Continuous simulation version of AGNPS model
ARS	Agricultural Research Service
EPIC	Erosion Productivity Impact Calculator
GEM	Generation of weather Elements for Multiple applications model
GLEAMS	Groundwater Loading Effects of Agricultural Management Systems
KINEROS	KINematic runoff and EROSion model
LISEM	LImburg Soil Erosion Model
MMS	Modular Modeling System
NLEAP	Nitrogen Leaching and Economic Analysis Package
NRCS	Natural Resources Conservation Service
PRISM	Parameter-elevation Regressions on Independent Slopes Model
RUSLE	Revised Universal Soil Loss Equation
SCS	Soil Conservation Service
SHE	Système Hydrologique Européean
SWAT	Soil and Water Assessment Tool
SWRRB	Simulator for Water Resources in Rural Basins
TOPAZ	TOPographic PArameteriZation model
USDA	United States Department of Agriculture
WEPP	Water Erosion Prediction Project

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