GIS-BASED COUPLING OF GLEAMS AND REMM HYDROLOGY: I. DEVELOPMENT AND SENSITIVITY

M. A. Tucker, D. L. Thomas, D. D. Bosch, G. Vellidis

ABSTRACT. *Movement of water from agricultural fields and into adjacent riparian areas is an important process in minimizing pollution for a large percentage of agricultural lands. Models have been developed for upland agricultural areas and for riparian zones. Creating a flexible structure for linking two different models is both desirable and needed for complete analysis of the systems. Since water is the primary mechanism for pollutant transport, creating a system which manages both surface and subsurface water movement is a first priority. An integrated model system was developed for joining the hydrologic portions of GLEAMS and REMM in a cascaded format to determine the fate of surface and subsurface water leaving an upland cultivated area and traversing a riparian forest. Data was managed within a GIS to aid in inputting and manipulating both spatial and nonspatial model parameters. Transfer of subsurface flow from the upland model to the riparian model was achieved through Darcy's equation. Partitioning of the flow was based on the hydraulic conductivity of the different layers and the depth of the water table. The model system was able to account for saturated zones encountered in the riparian area by raising the water table. The model system responded as would be expected under relatively extreme changes in precipitation for both shallow groundwater levels and runoff. The model system also exhibited expected behavior under different leaf area index (LAI) parameters within the forest. The shallow groundwater levels and runoff were not drastically affected, but the levels of response were within the range of expectations.*

Keywords. *Hydrologic modeling, Water table, Hydrology, Runoff, Hydraulic conductivity.*

The contamination of surface and groundwaters from non-point sources is being addressed by many national and state agencies, as well as private and public institutions. Best management practice (BMP) guidelines are needed to reduce nutrient and pesticide runoff and leaching from all agricultural areas.

Several models have been developed to aid in predicting and assessing nutrient and pesticide movement within an agricultural field or an agriculturally influenced watershed. Models are typically either on a watershed-scale such as AGNPS (Agricultural Non-point Source) by Young et al. (1989) or a field-scale such as GLEAMS (Groundwater Loading Effects of Agricultural Management Systems) by Leonard et al. (1987). Watershed-scale models tend to be less specific with regard to field-scale processes, but can integrate multiple land uses. Field-scale models are usually representative of homogenous, single soil and crop applications, but are less likely to be capable of managing multiple land uses in a single simulation. In most available models, the hydrology component is the driving force behind the transport of nutrient and/or pesticide pollutants. Therefore, if the hydrology of a model system functions reasonably well, the chemical components are more likely to be reasonable.

One idea under consideration as a best management tool is the development or enhancement of forested riparian (streamside) buffers between agricultural fields, or livestock areas, and streams. These riparian forest buffer systems (RFBS) are usually between fields and streams and help in controlling non-point sources of pollution (Lowrance et al., 1985). This buffering includes the filtration of nutrients and pesticides from upland agricultural areas through both surface and subsurface lateral flow. The size and characteristics of these riparian buffers necessary to meet particular water quality goals on different landscapes are still not well defined. The Riparian Ecosystem Management Model (REMM) was developed to help determine and evaluate riparian buffer effectiveness for achieving these water quality goals (Lowrance et al., 2000).

The potential to use two models such as GLEAMS and REMM in a cascaded format would allow evaluation of best management practices in an agricultural field and a downslope riparian area. The "cascading" process implies that the models would not be run simultaneously. The upland model would be run first, and then followed by the riparian or downslope model. Outputs from the upland model would be used as inputs for the riparian model.

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The authors are **Michael A. Tucker** (former Graduate Assistant), Design Engineer, Kelly Manufacturing Co., Tifton, Ga.; **Daniel L. Thomas**, **ASAE Member Engineer**, Professor, Biological and Agricultural Engineering Dept., University of Georgia, Tifton, Ga.; **David D. Bosch**, **ASAE Member Engineer**, Research Hydraulic Engineer, USDA, ARS, Southeast Watershed Research Laboratory, Tifton, Ga.; **George Vellidis**, **ASAE Member Engineer**, Associate Professor, Biological and Agricultural Engineering Dept., University of Georgia, Tifton, Ga. **Corresponding author:** D. L. Thomas, University of Georgia, Biological and Agricultural Engineering Dept., Tifton, GA 31793-0748, phone: 912.386.3377, fax: 912.386.3958, e-mail: <thomasdl@tifton.cpes.peachnet.edu>.

Cascading does not provide the best feedback alternatives, but it is the most logical approach with two complex models that are not designed to function as one system. Gerwig et al. (1998) evaluated the capabilities of both GLEAMS and REMM to estimate nutrient movement from a spray field (waste application) and through a riparian forest. Their results indicate that the preliminary version of REMM (at the time) had good capabilities, but the interface for entering data and management of data between the models was time consuming. The potential for improving data management between the models and for output analysis (from either model) will greatly enhance the utility of this combined system. Inamdar et al. (1999) evaluated REMM capabilities under riparian conditions in south Georgia. REMM functioned adequately even though it did not respond as quickly to events as compared to field measured conditions. In that work, field-measured data were used as inputs to the model for upland conditions (subsurface flow and runoff).

Most water quality and management models require various input parameters such as soil characteristics, slopes, crop covers, etc. A valuable tool for organizing these input parameters, as well as displaying the model results, is a software package called Geographical Information System (GIS) that allows the incorporation of spatial data (maps) with non-spatial attributes (e.g., model input parameters). Integrating a GIS with water quality model aids in providing a quick view of results or parameters on a spatial scale. Vieux et al. (1989) state that without the aid of integrated systems (GIS and models), planners must assemble large amounts of data and relate the data (soil types, slopes, etc.) to spatial entities using maps. Kosky and Engel (1997) point out that the data required for hydrologic and water quality model inputs are inherently spatially variable, thus making the use of such models without the aid of a GIS somewhat prohibitive.

The integration of GIS and water quality models allows for the quick assessment of “what if” scenarios. If non-constant input parameters for models are left open-ended, that is, with the capability to modify or change parameters, then hypothetical best management practices can be analyzed.

The interfacing of water quality models with a GIS is not a new concept. Oslin et al. (1988) developed STREAMS (Soil, Transport, Rainfall, Erosion, and Mapping System) to facilitate watershed spatial management. They transferred previously digitized file maps in vector format into raster-based GIS files. Attribute data, which includes the descriptive parameters, from these files were used as inputs to the USLE, the HEC2 hydrologic model, and the HEC6 sediment transport model. Landsat Thematic Mapper (TM) and SPOT multi-spectral satellite images were used to produce the original spatial component of the files. The objectives of that project were to determine changes in land use over time, to predict average soil loss within a basin, to locate possible high erosion and sedimentation sites, and to delineate flood plains using artificially generated rainfall events.

Stuebe and Douglas (1990) used a GIS with the Soil Conservation Service’s runoff equation (USDA, SCS, 1964) to predict runoff from six watersheds. Due to the simplicity of the model, the solutions to the equation were performed within the GIS eliminating need for a GIS/model interface. The GIS used in this project was GRASS (Geographic Resources Analysis Support System) which is a public domain raster format GIS developed by the U.S. Army Construction Engineering Laboratory. Different data layers were created to calculate and store the equation parameter values in each cell. Then the values in these layers were used to calculate the runoff volume for each raster cell. The watersheds were delineated using digital elevation data from the U.S. Geological Survey. Vegetative land cover information was required to attain the runoff curve number. These data were entered into the GRASS GIS using LANDSAT multi-spectral scanner images. Land use data also required for calculating the curve number were obtained from aerial photographs. The resolution of these spatial data was 100 m.

Zhang et al. (1990) used the CMLS (Chemical Movement in Layered Soils) model (Nofziger and Hornsby, 1986) in conjunction with the vector-based ARC/INFO GIS to predict chemical movement through the root zone. The ARC/INFO’s Simple Macro Language (SML) enabled the interfacing of the GIS with the CMLS model such that the operation of the interface was transparent to the user. Programs were written with the SML that allowed user-specified chemically related input data, data exportation from the GIS database to the model in proper format, importation of the model output into the GIS, and matching of the model output to the corresponding polygon (watershed). By keeping the GIS and the model separate, the capability to use the GIS database with different models was retained.

De Roo et al. (1989) used a raster-based GIS and the ANSWERS (Areal Nonpoint Source Watershed Environment Response Simulation) model (Beasley and Huggins, 1982) to assess surface runoff and erosion within a watershed. They found that the raster-based GIS worked well with the distributed parameter ANSWERS model in passing the cell data to-and-from the cell-based model. However, not all model input data were available at a resolution required by the model.

GLEAMS

GLEAMS (Leonard et al., 1987) is a mathematical, computer-based model developed for use with field-sized areas to assess agricultural management effects on water and chemical movement in surface runoff and through the plant root zone. The hydrologic component of GLEAMS establishes the foundation for assessing pesticide and/or nutrient movement. GLEAMS allows the input of parameter data and the output of model analysis through DOS type files (Knisel et al., 1993). Input parameters include information on soil profile characteristics, daily rainfall amounts, climatic data, crop cover, field geometry, and land management practices. The model allows the user to specify the frequency of model output and changes in input over the simulation period. During a prolonged model run, parameters that may affect hydrology dynamics, such as crop rotations and irrigation applications, can be updated. Hydrologic outputs can be assessed over days, months, years, or individual storm events. The GLEAMS model is being used extensively around the world and has been verified under many different physiographic conditions and compared to many other models (Reyes and Cecil, 1997; Smith et al., 1991; Ma et al., 1998;

Shirmohammadi and Knisel, 1994). Based upon the model's extensive use around the world, it was a logical choice for a field-scale model in this study.

REMM

The Riparian Ecosystem Management Model (REMM) was developed by Lowrance et al. (2000) for predicting the influence of riparian forest ecosystems on water quality. The REMM model is intended to determine the effectiveness of riparian forests, under varied management practices, in reducing non-point nutrient and pesticide outputs from upland areas. It is especially suited for those riparian areas that comply with the Riparian Forest Buffer System (RFBS) specifications suggested by the U.S. Forest Service (Welsch, 1991).

A RFBS is typically made up of three zones (fig. 1). Zone 1, located directly adjacent to a stream or impoundment, consists of permanent vegetation. This zone is usually at least 4.6 m wide and is not disturbed. Zone 2, located upslope and adjacent to zone 1, is the widest of the three zones with a minimum of 18.3 m. Forest management practices are applied in this zone. Zone 2 provides the bulk of the vegetation for filtering pollutants. Zone 3, located upslope between zone 2 and the cropland area, has a recommended minimum width of about 6.1 m. This zone is normally a grassed buffer strip. The primary purpose of this zone is to disperse surface flow from the upland area for more uniform flow into zone 2. Within REMM, each zone is divided into five vertical layers (a plant layer, a litter layer, and three soil layers). Various input parameter values are required for each of these layers.

The model uses a daily time-step and is designed to simulate surface and subsurface hydrology, nutrient dynamics, and plant growth. The model simulates both physical and biological processes (Lowrance et al., 2000). Input data to be supplied by the user include a site description (including area dimensions and slope), daily weather data (temperatures, precipitation, and solar radiation), soil properties, vegetation characteristics, and upland inputs. The water balance for water movement through, and storage within, the riparian area includes considerations of interception, evapotranspiration, and surface and subsurface flow. The REMM version used in this study contained only the hydrologic functions incorporated by 1993 (Altier et al., 1992). Changes to the model in recent years have created some slight modifications to the hydrologic processing as well as to carbon and nutrient cycling (Lowrance et al., 2000). However, the functional capabilities of the hydrology model are virtually the same as the current version available for distribution.

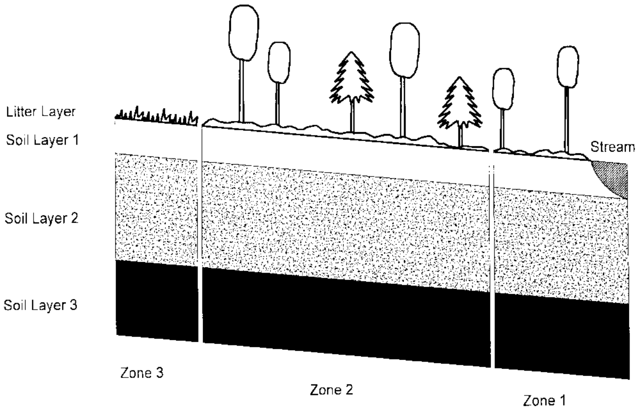


Figure 1–Illustration of a riparian area as defined in REMM.

OBJECTIVES

The purpose of this project was to use the hydrology components of water quality models GLEAMS and REMM in a cascaded format to assess the capabilities of this approach in representing field conditions of hydrologic outflow from upland agricultural cropland through a downslope riparian zone. The initial determination of whether the system is capable of representing field conditions is through a limited sensitivity analysis. If the response of the system to changes in selected parameters is not representative of what would be expected, then the model system would be deemed "nonrepresentative". One other requirement of the system is that model input parameters are to be readily accessible using GIS databases and spatial representation features. The critical objective of this project is to create an integrated system for flexible management of data between the models without losing the integrity of model relationships. In addition, the models were to remain intact to allow new versions to be added to the system in the future with nutrient and pesticide features.

METHODS

The project schematic of the hardware and software components required for the model system is illustrated in figure 2. The model systems and GIS were incorporated on an 80486DX microprocessor-based personal computer operating at 33 megahertz and a 500 megabyte hard drive for file/map coverage storage. A 43 × 61 cm digitizing tablet was used to convert map hard copies to digital format.

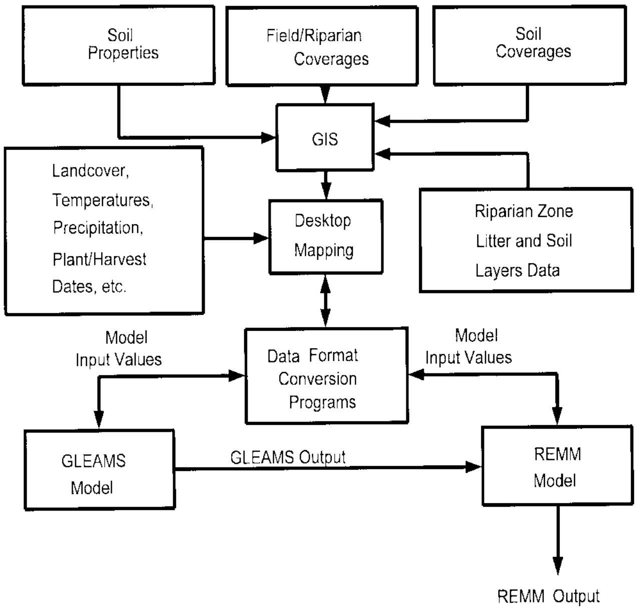


Figure 2–Project schematic illustrating existing and created components.

The SPatial ANalysis System (SPANS) was the GIS used in the project. Using a “quadtree” data modeling format, SPANS allows varying raster cell sizes to store map coverages and performs data compression internally (thus saving file storage space in comparison to a typical raster format with equally sized cells). A desktop mapping software package called MAP was used in conjunction with the GIS (Intera Tydac, 1992). Also, SPANS has routines to allow digitizing of map hard copies.

All custom programs used in the project were written in the C programming language. The custom programs and the off-the-shelf software, including the GIS and desktop mapping packages, were run within the OS/2 operating environment.

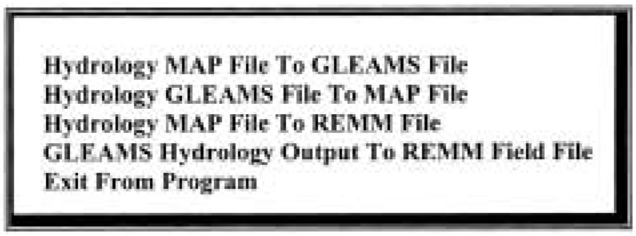
MODEL PARAMETER TABLES

Model input parameter template tables were constructed using the MAP software’s spreadsheet capabilities. Tables were built for both GLEAMS and REMM model input parameter files. The input parameter names used in the GLEAMS table are identical to those used in the GLEAMS documentation (Knisel et al., 1993).

Each line of the GLEAMS input values table is for one upland area (i.e., the values for one GLEAMS hydrology input file). These tables allow the user to quickly make changes to the input values of several upland areas without opening each individual GLEAMS hydrology input file for each area. The template tables provided the framework for developing soil characteristic tables and riparian soil layers and zone tables within the GIS. They also provided a starting point for development of the GIS-to-model data formatting program.

A data formatting program was required for the transformation of the model input parameters in the desktop mapping table to the format required by the model input files. The opening menu of the C program is shown in figure 3. For details on the subroutines and programs used to reformat data, the reader is referred to Tucker (1998) and Tucker et al. (1994). It is important to note that these programs were designed to add lines of parameter values as required. For example, the GLEAMS hydrology input file is not fixed but instead depends on certain input parameters such as the number of crop rotations, soil horizons or years of simulation. The subroutine was designed to add only those required lines of parameter values.

The GLEAMS input files also need input values for climate-related data of mean monthly minimum temperature, maximum temperature, solar radiation, wind movement, and dew point temperature. Because these values would be the same for several upland areas, they were not included in the MAP table of model parameters. Instead one field of the table is used to specify the name of the file in which this data is located. The program subroutine uses this field to locate the file and input the climatic data when building the model input file(s). This procedure allows several upland areas to use the same climatic data and prevents repeating the same data for each upland area in the table.



Hydrology MAP File To GLEAMS File
Hydrology GLEAMS File To MAP File
Hydrology MAP File To REMM File
GLEAMS Hydrology Output To REMM Field File
Exit From Program

Figure 3–Opening menu of data transfer program.

The REMM model hydrology component requires four input files. They are weather, zone inputs, upland area inputs, and constants files. Procedures were developed for building only the constants files for each riparian area. The weather and zone input files contained data such as daily rainfall amounts, evaporation, minimum and maximum air temperatures, and soil temperatures that could be used in several different riparian areas. These files can be constructed using any text editor. The upland area inputs come from the output of the upland model, GLEAMS. The REMM constants input file contains parameters which provide site-specific information for zones one, two, and three of a riparian area. Some of these parameters are zone length and width; porosity, field capacity, thickness, bulk density, clay, sand, and silt content of each of the three soil layers; and plant leaf area index. The REMM MAP table file was constructed with each line of the table containing the model input parameters for one riparian zone. One column of the table was used to identify the riparian area that each zone represents. That is, for each riparian area represented in the table, there were three lines of input constants, one for each of the area’s three riparian zones.

GIS MODELING

The SPANS GIS contains several intrinsic commands for performing table or map modeling. The GIS also provides a programming language which allows the user to create custom modeling equations. The flowchart in figure 4 gives an overview of the procedures and steps used in GIS modeling for building a portion of the GLEAMS hydrology parameter files. Many of the GLEAMS model hydrology input parameters are directly related to soil characteristics. Therefore, the approach was to use the GIS overlay and analysis functions to determine and assemble the model’s soil-related input parameters for each upland area. Other required input parameters, dealing mainly with cropping practices, were then added manually into the table already containing the GIS-obtained soil parameter inputs.

An equation was written to isolate upland areas (agricultural fields) in a map table containing both upland areas and riparian zones. This resulted in a new table containing only upland areas. GLEAMS assumes that the soil for a given upland area is homogeneous. Because in reality, this may not be the case, GIS modeling equations were written to determine the dominant soil in an area. The criterion used was to find the soil that covered the largest percentage of each upland area. The upland areas map can overlay the soils map to create a new map by “cookie-cutting” the soils map with the upland areas map. Equations were written to select the dominant soils of each upland area and assign the soil type number to the upland area in the upland area table. A relational joint equation was written that appends the soil characteristics from a soils parameter lookup table to the field table. In the equation, the soil type number is used to relate the

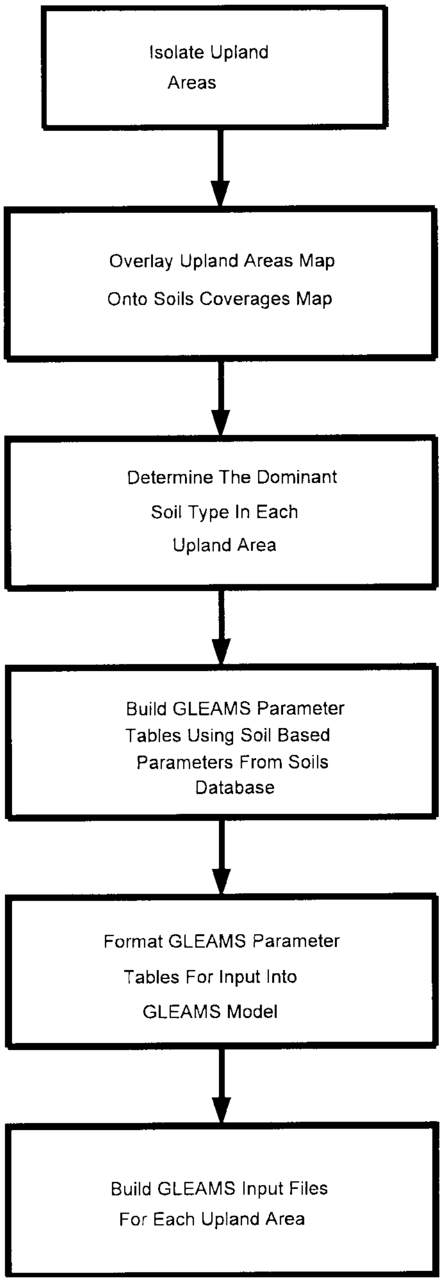


Figure 4–Steps taken to input GLEAMS model input files.

appropriate record in the soils parameter lookup table with the dominant soil in the upland area table.

Once the soil characteristics data are appended to the field table, the table is then transferred to the desktop mapping environment where the remainder of the GLEAMS input parameter values are added to each upland area. Each line (or record) of the table contains parameter input values for one upland area.

The first step in GIS modeling for REMM parameter files, similar to GIS modeling for GLEAMS files, is to isolate the riparian area data from the upland area data. A GIS program subroutine was written to do this. After running the subroutine, a new table is formed containing only geographical data and some of the attribute values for riparian areas. Each line of the table contains data for one of the three zones of a riparian area.

Next, parameter headings and columns for some of the REMM input variables along with an indexing column were appended to the new table. The values in this column are used to append model input variables relationally from other preconstructed parameter value lookup tables.

Three parameter value lookup tables were constructed: one each for plant and litter layer values, and one for soil parameter values (see fig. 1). Each line of these tables contains specific parameter values for a particular plant, litter or soil layer. A modeling equation was written which allows the user to synthesize the five required layers for each riparian zone from the parameter value lookup tables into one table.

The above approach allows the user to “piece together” the five sets of layer values for each riparian zone. It also diminishes duplicating of data in cases where two riparian zones might have some identical and some different layers. For example, two zones could have the same type of plant and litter layers but one or more different soil layers.

INTEGRATING GLEAMS AND REMM

A subroutine was developed to input into REMM the daily subsurface and surface hydrology output values from GLEAMS. The subroutine modifies the subsurface values before passing them to the REMM model field inputs file.

The GLEAMS model simulates surface water movement and vertical movement of water through the plant root zone; however, it does not account for lateral subsurface movement of water. Hubbard and Sheridan (1983) note that lateral subsurface water movement occurs in areas such as the Georgia Coastal Plain that have underlying soil horizons with low permeability. Darcy’s Law for saturated flow was used to divide the flow leaving the upland root-zone between deep percolation and lateral flow which moves into riparian areas:

$$Q = KA\,\frac{\Delta H}{L} \qquad (1)$$

where

Q = volume rate of flow ($l^3\,t^{-1}$)
K = saturated hydraulic conductivity ($l\,t^{-1}$)
A = cross-sectional area (l^2)
ΔH = head difference (l)
L = length of the flow section associated with the head difference (l)

The GLEAMS-to-REMM subroutine performs two calculations for each daily percolation input from GLEAMS. First, the subroutine uses the saturated hydraulic conductivity of the soil horizon just below the root-zone to determine how much of the daily percolation penetrates the horizon and exits to groundwater. Then using the saturated hydraulic conductivity of the soil layer(s) in the root-zone for K in equation 1, the subroutine estimates how much of the remaining GLEAMS output moves laterally into the riparian areas. Because GLEAMS gives the percolation values in area-depth units for the entire upland area, the subroutine must divide the output among the partitioned areas whose outputs influence a particular riparian zone. The subroutine uses the percentage of the total area that a partitioned area covers multiplied by the total subsurface output to calculate the amount.

The slope and length of the upland areas are used to determine the head difference, ΔH, and the length, L, variables in equation 1. The width of the cross-sectional area is calculated by dividing the upland area by the length.

In cases where large rainfall amounts occur, the upland area's soil may become saturated to levels well above the impeding soil layer. In these cases, the saturated area may traverse several soil horizons, each having different saturated hydraulic conductivities. The subroutine accounts for these different conductivities and moves the water laterally into the riparian areas at different rates depending on the saturated conductivity of the horizon. This adjustment to the water movement based on saturated areas encountered in downslope areas is functionally accounted for by raising the water table depth.

The subroutine simulates the water moving into the riparian areas in stacks of horizontally long, vertically short rectangles. The lengths of the rectangles are determined by the saturated conductivity of the soil horizon they reside in, and the heights by the amounts of daily percolation estimated by GLEAMS.

RESULTS

SENSITIVITY ANALYSIS

A limited sensitivity analysis was used to evaluate the response of the model system to changes in parameters to evaluate whether the model integration techniques provided reasonable results. The data set used in the sensitivity analysis was associated with a riparian field site located near Tifton, Georgia, specifically on the Gibbs Research Farm of the Coastal Plain Experiment Station (Tucker et al., 2000). This research site includes forested riparian areas (clear-cut, thinned, and mature) with monitoring of surface and subsurface flow from the upland agricultural area, through the grass buffer and within the riparian forest zones. The soils at this site are predominately loamy sands (less than 4% slope) and the crop grown in the upland area during the study period was field corn only. Characteristics of the site are indicated in Lowrance et al. (1997), and Bosch et al. (1996). Initial parameters for the site conditions are indicated in Tucker et al. (2000). The specific parameters evaluated in the sensitivity analysis were precipitation and leaf area index (LAI). The LAI sensitivity analysis was selected since the field site to be used for field data verification was represented by different riparian management levels (mature, thinned, and clear-cut). Response to different levels of precipitation would be expected to provide the greatest impact on outflow and water table levels. The "effect" of parameter changes were evaluated by the average monthly shallow groundwater levels (associated with zone 2 of the riparian area) and monthly total runoff. For all cases, the rainfall was applied to the upland and riparian areas, but only the response in the riparian area are illustrated.

For the precipitation analysis, measured amounts between April 1992 and August 1994 were used as the base or 100% values. For the sensitivity analysis, 50% and 150% of measured precipitation were compared to the 100% amount. It would be expected that a reduction in rainfall should have a direct impact on lowering subsurface water levels and reducing surface runoff. The nature of management within the forest (such as clear-cut, thinned, young, mature, burned) in zone 2 of a riparian area will influence the LAI. Three LAI values for the forest only were used in this particular analysis: 1.5, 3.0, and 4.5 LAI are representative of clear-cut, thinned, and mature forest for this region. The LAI values for the upland corn were not varied. The expected subsurface water level response would be lower water levels as the LAI increased. Runoff rates would be expected to decrease as the LAI increases. For all LAI simulations, the precipitation amount used was 100% of measured precipitation from the site during the period of interest.

Figure 5 illustrates the changes in shallow groundwater levels for an assumed mature forest (LAI 4.5) for the three precipitation rates. In this particular case, the initial shallow groundwater level was the same for each precipitation scenario. The figure indicates that the model is responsive to precipitation changes from 50 to 100% and from 100 to 150%. It is interesting to note that the disparity between the 100 and 150% amounts are greater during the crop growth period, indicating that the model system is sensitive to the accelerated water uptake of the forest and crop during the warm/growing season. The response of the water level under 50% precipitation implies that the water below 1.8 m from the surface was not readily accessible to the plants (after the first year) and that this lower rainfall amount did not significantly contribute to shallow groundwater recharge (was used mainly for plant uptake). The greatest groundwater level differential between the 100 and 150% precipitation amounts was between August and November in 1993. This average 0.6 m difference in the water level was created with about 140 mm of additional precipitation (150% to 100%). Obviously, this water table increase was a combination of excess water from the upland area and direct input from the riparian area. This small amount of additional precipitation over a four month period greatly impacted the shallow groundwater level, and could greatly influence the movement of chemicals and nutrients within shallow groundwater. The response characteristics of the combined GLEAMS and REMM model under LAI conditions for clear-cut and thinned forest conditions were very similar to these results.

Figure 6 illustrates the total monthly runoff volumes under an assumed mature forest riparian area for the 100 and 150% precipitation amounts. The results from the 50% of measured precipitation were not included because runoff amounts for each month were zero. The model system was highly sensitive to precipitation amounts. In winter months where large amounts of precipitation occurred (such as January 1993), as much as half the rainfall left the site as runoff when 150% of measured precipitation was applied. During summer (growing season) months in 1994 where precipitation was even higher, runoff was a much smaller percentage. The model system was able to reflect expected changes in runoff under varying conditions of plant water up-take by crops and trees and interception of precipitation by the plant canopies.

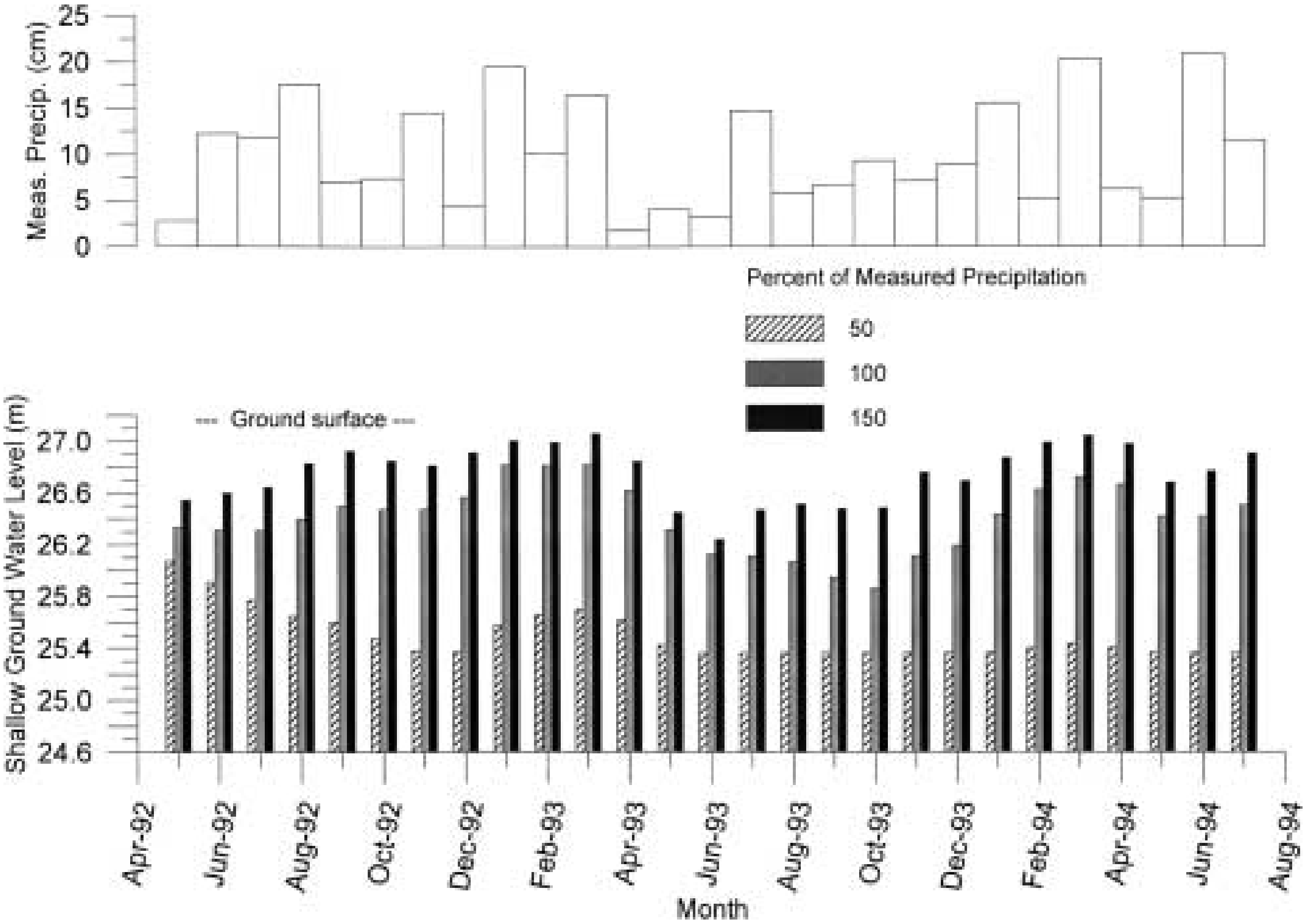


Figure 5–Simulated shallow groundwater level response for an upland agricultural area contributing to an assumed mature forest at 50, 100, and 150% of measured precipitation.

The effects of LAI on shallow subsurface water levels for the assumed mature forest are illustrated in figure 7. Changes in LAI appear to have a relatively minimal effect on shallow groundwater levels during the growing season and virtually no effect during the dormant season. As is expected, the LAI is tied to the evapotranspiration rate which decreases as temperature decreases. Depending on whether plant needs are being met within the unsaturated zone (as in winter months), the water table should not be affected by differences in LAI. However, as plant uptake increases during summer months, the shallow subsurface water levels should provide some of the water requirement, thus lowering the water table. The model system appears to be functioning as expected.

Estimated average monthly runoff volumes are illustrated in figure 8. Simulated runoff only occurred in six different months during the two-year period indicating that the model system expected most of the water to infiltrate into the soil. For those displayed runoff events, a slight variation in runoff amount was evident in only two months (January and March 1994). In these two months, the runoff rates increased as the LAI decreased. The changes in plant-water uptake due to a lower LAI increases the water table level and unsaturated water content, thus reducing soil intake (increasing runoff). Although the runoff results from the model system were not very sensitive to LAI, natural systems would not be expected to be very sensitive to LAI differences, especially during the indicated winter months.

CONCLUSIONS

An integrated model system was developed for joining the hydrologic portions of two water quality models. The upland model (GLEAMS) and a riparian area model (REMM) can be applied in a cascaded format to determine the fate of surface and subsurface water leaving an upland cultivated area and traversing a forested riparian area. A GIS was implemented to aid in inputting, managing, and manipulating both spatial and nonspatial model input parameter data. Independent programs were developed to retrieve model input data files from the GIS, properly format them, and input them into the models' input data files. Additionally, programs were written to retrieve output values from the field scale model and input them into the riparian model's upland input files. Transfer of subsurface flow from the upland model to the riparian model was achieved through Darcy's equation. Partitioning of the flow was based on the hydraulic conductivity of the different layers and the depth of the water table. The model system was able to account for saturated zones encountered in the riparian area by raising the water table.

Using the GIS for inputting and managing model input data proved advantageous considering the large number of

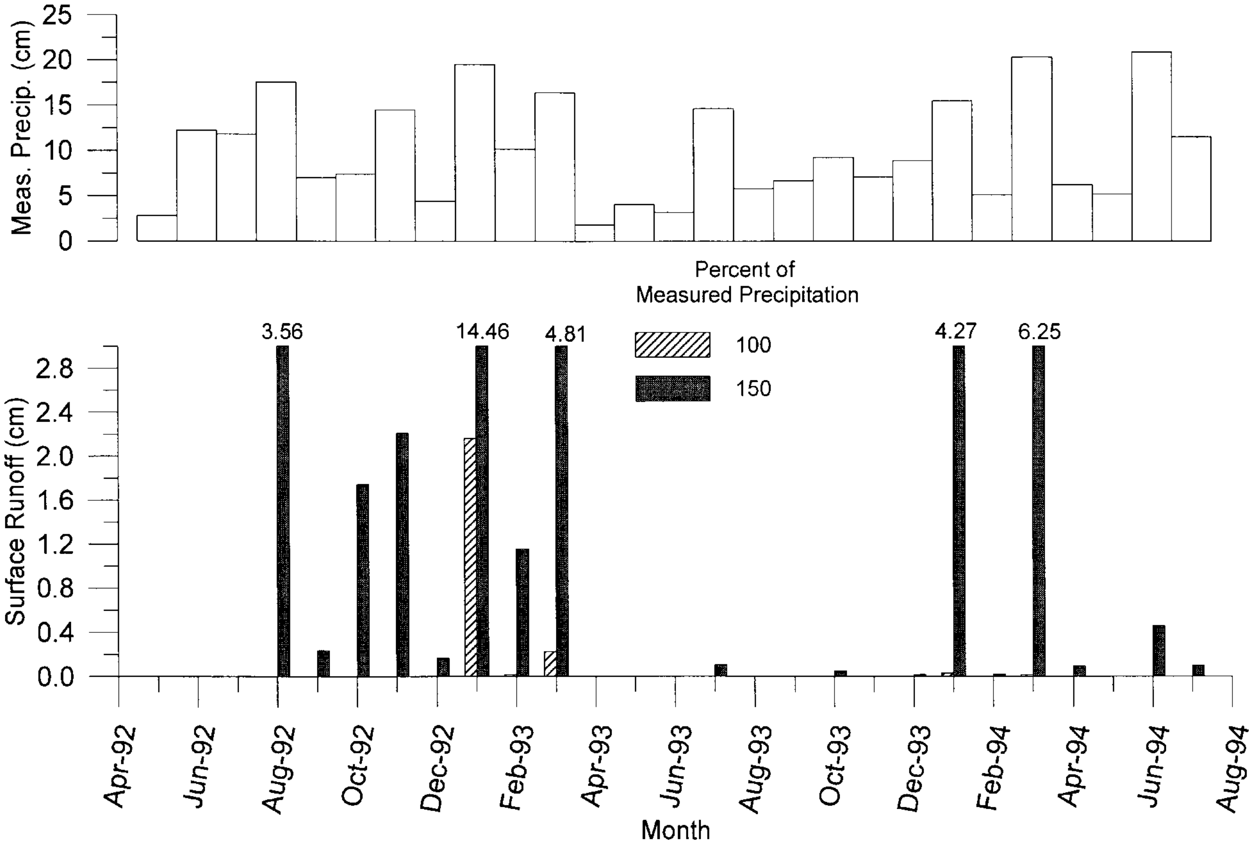


Figure 6–Simulated surface runoff from the managed forest zone for an upland agricultural area contributing to a mature forest under precipitation amounts of 100 and 150% of measured.

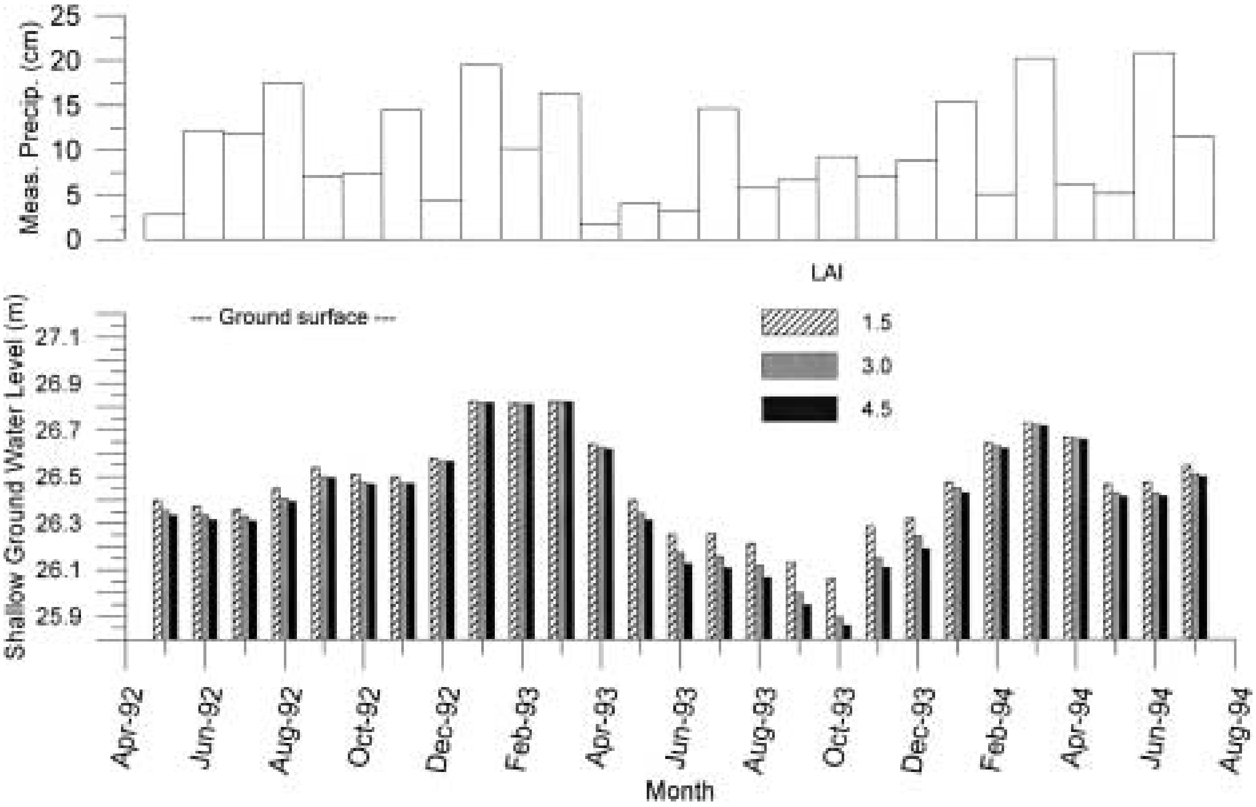


Figure 7–Simulated shallow groundwater levels under forest canopy leaf area index (LAI) values of 1.5, 3.0, and 4.5 (upland agricultural LAI values were not varied).

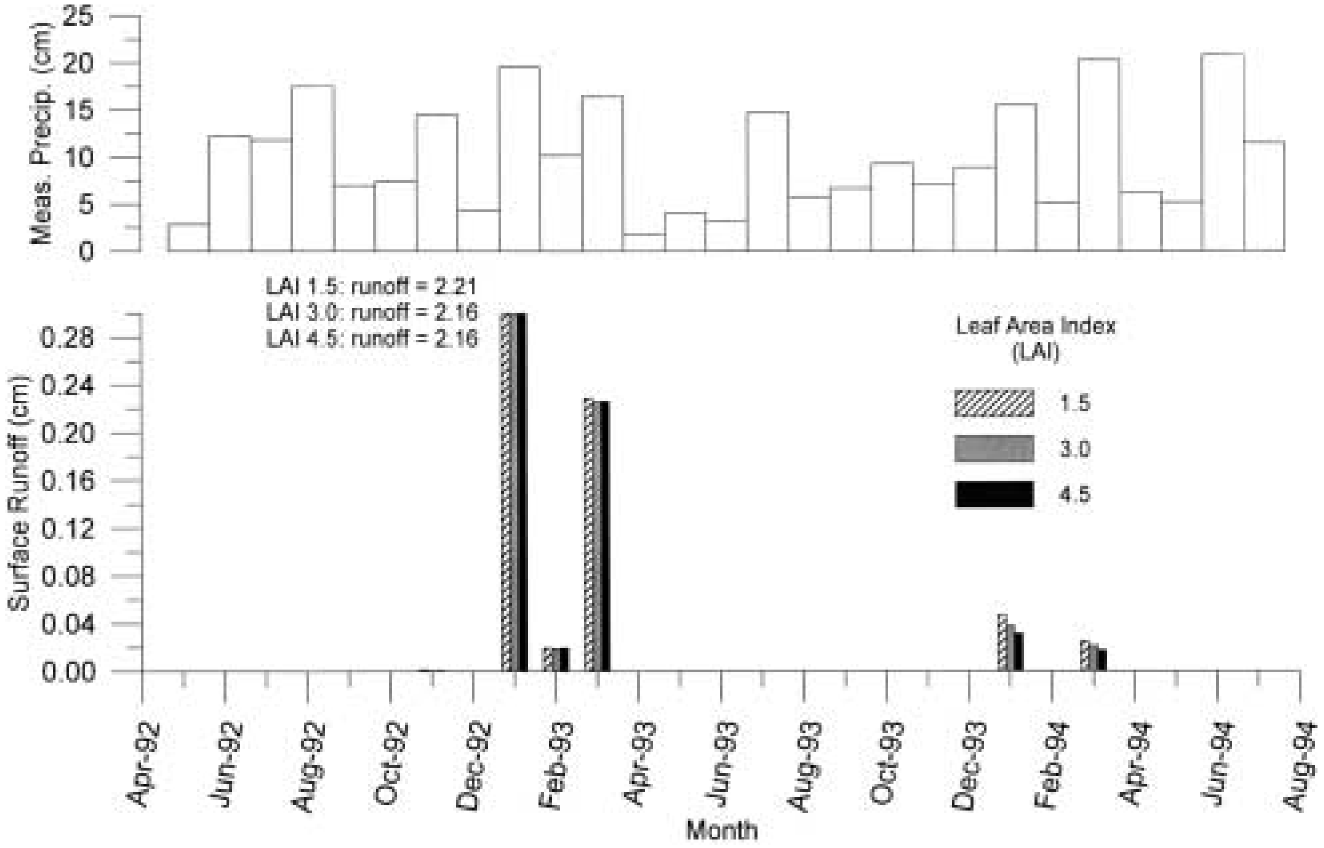


Figure 8–Simulated surface runoff under forest canopy leaf area index (LAI) values of 1.5, 3.0, and 4.5 (upland agricultural LAI values were not varied).

input parameter values required for each model. In the GIS, the model input data files for several modelled areas could be viewed and modified within a single environment. Also the geographical site, upland area or riparian zone, that the input value(s) were related to could be visually located.

A shortcoming in this study was the lack of integration between the components used, i.e., the GIS, the models' front-end input tables, and the independent data formatting programs. However, with the graphical user interface features and multitasking capabilities of today's personal computers, the complexity of changing between different software environments is reduced.

The model system responded as would be expected under relatively extreme changes in precipitation for both shallow groundwater levels and runoff. The model system also exhibited expected behavior under changes in LAI. The shallow groundwater levels and runoff were not drastically affected, but the levels of response were reasonable.

This study shows that using a GIS for organizing model input parameter data is extremely useful. If several iterations of model executions are to be performed to investigate best management practices (BMP), in a limited amount of time, then the use of a GIS becomes more practical and perhaps essential. The SPANS package does provide the essential characteristics and capabilities for integrating model parameters. Alternative GIS systems would be expected to provide similar capabilities. Incorporation of the chemical components of the two different models and analyzing those responses would be beneficial to evaluating overall model system capabilities.

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REFERENCES

Altier, L. S., R. R. Lowrance, R. G. Williams, J. M. Sheridan, D. D. Bosch, R. K. Hubbard, W. C. Mills, and D. L. Thomas. 1992. An ecosystem model for the management of riparian areas. *Proc. Conference on Riparian Ecosystems in the U.S.* Washington, D.C.: USDA, ARS.

Beasley, D. B. and L. F. Huggins. 1982. ANSWERS (Areal nonpoint source watershed environment response simulation) users manual. U.S. EPA-905/9-82-001. U.S. Environmental Protection Agency, Region V.

Bosch, D. D., J. M. Sheridan, and R. R. Lowrance. 1996. Hydraulic gradients and flow rates of a shallow Coastal Plain aquifer in a forested riparian buffer. *Transactions of the ASAE* 39(3): 865-871.

De Roo, A. P. J., L. Hazelhoff, and P. A. Burrough. 1989. Soil erosion modeling using 'ANSWERS' and geographical information systems. *Earth Surface Processes & Landforms* 14(6&7): 517-532.

Gerwig, B. K., K. C. Stone, R. Williams, D. W. Watts, and J. M. Novak. 1998. Using GLEAMS and REMM to estimate nutrient movement from a spray field and through a riparian forest. ASAE Paper No. 98-2213. St. Joseph, Mich.: ASAE.

Hubbard, R. K. and J. M. Sheridan. 1983. Water and nitrate-nitrogen losses from a small, upland, Coastal Plain watershed. *J. Environ. Qual.* 12(2): 291-295.

Inamdar, S. P., J. M. Sheridan, R. G. Williams, D. D. Bosch, R. R. Lowrance, L. S. Altier, and D. L. Thomas. 1999. Riparian ecosystem management model (REMM): I. Testing of the hydrologic component for a coastal plain riparian system. *Transactions of the ASAE* 42(6): 1679-1689.

Intera Tydac Technologies Inc. 1992. Map User's Guide. Intera Tydac Technologies Inc. Nepean, Ontario, Canada.

Knisel, W. G. (ed.). 1993. GLEAMS: Groundwater Loading Effects of Agricultural Management Systems. UGA-CPES-BAED Pub. No. 5.

Kosky, K. M., and B. A. Engel. 1997. Evaluation of three distributed parameter hydrologic/water quality models. *Proc. Mini-conference on the Applications of Emerging Technologies in Hydrology*, 37-40. St. Joseph, Mich.: ASAE.

Leonard, R. A., W. G. Knisel, and D. A. Still. 1987. GLEAMS: groundwater loading effects of agricultural management systems. *Transactions of the ASAE* 30(5): 1403-1418.

Lowrance, R. R., L. S. Altier, R. G. Williams, S. P. Inamdar, J. M Sheridan, D. D. Bosch, R. K. Hubbard, and D. L. Thomas. 2000. REMM: The riparian ecosystem management model. *J. Soil & Water Cons.* 55(1): 27-34.

Lowrance, R. R., R. A. Leonard, and J. M. Sheridan. 1985. Managing riparian ecosystems to control non-point pollution. *J. Soil & Water Cons.* 40(1): 87-91.

Lowrance, R. R., G. Vellidis, R. D. Wauchope, P. Gay, and D. D. Bosch. 1997. Herbicide transport in a managed riparian forest buffer system. *Transactions of the ASAE* 40(4): 1047-1057.

Ma, Q. L., R. D. Wauchope, J. E. Hook, A. W. Johnson, C. C. Truman, C. C. Dowler, G. J. Gascho, J. G. Davis, H. R. Sumner, and L. D. Chandler. 1998. GLEAMS, OPUS, and PRZM-2 model predicted versus measured runoff from a Coastal Plain loamy sand. *Transactions of the ASAE* 41(1): 77-88.

Nofziger, D. L., and A. G. Hornsby. 1986. A microcomputer-based management tool for chemical movement in soil. *Applied Agric. Res.* 1: 50-57.

Oslin, A. J., R. A. Westsmith, and D. S. Morgan. 1988. STREAM: A basin and soil erosion model using CADD, remote sensing and GIS to facilitate watershed management. *Proc. 1988 Int. ASAE Symposium Modeling Agriculture, Forest, and Rangeland Hydrology.* St. Joseph, Mich.: ASAE.

Reyes, M. R., and K. D. Cecil. 1997. Comparing GLEAMS, RUSLE, EPIC, and WEPP soil loss predictions with two years of observed data. ASAE Paper No. 97-2120. St. Joseph, Mich.: ASAE.

Shirmohammadi, A., and W. G. Knisel. 1994. Evaluation of the GLEAMS model for pesticide leaching in Sweden. *J. Environ. Sci. Health* A29(6): 1167-1182.

Smith, M. C., A. B. Bottcher, K. L. Campbell, and D. L. Thomas. 1991. Field testing and comparison of the PRZM and GLEAMS models. *Transactions of the ASAE* 34(3): 838-847.

Stuebe, M. M., and M. J. Douglas. 1990. Runoff volume estimation using GIS techniques. *Water Resour. Bull.* 26(4): 611-618.

Tucker, M. A. 1998. Coupling of hydrology components of the GLEAMS and REMM water quality models using a GIS. M.S. thesis. Athens, Ga.: University of Georgia.

Tucker, M. A., D. L. Thomas, L. S. Altier, and D. D. Bosch. 1994. GIS interfaced with field & riparian zone models. ASAE Paper No. 94-2151. St. Joseph, Mich.: ASAE.

Tucker, M. A., D. L. Thomas, D. D. Bosch, and G. Vellidis. 2000. GIS-based coupling of GLEAMS and REMM hydrology: II. field test results. *Transactions of the ASAE* 43(6): 1535-1544.

USDA, SCS. 1964. National Engineering Handbook, Hydrology, Section 4, Part 1, Watershed Planning. Washington, D.C.: USDA, SCS.

Vieux, B. E., L. P. Herndon, and R. Liston. 1989. GIS and water quality modeling for agricultural resource management systems. ASAE Paper No. 89-2184. St. Joseph, Mich.: ASAE.

Welsch, D. J. 1991. Riparian forest buffers. Function and design for protection and enhancement of water resources. USDA Forest Service, Northeastern Area, Radnor, Pa. NA-PR-07-91.

Young, R. A., C. A. Onstad, D. D. Bosch, and W. P. Anderson. 1989. AGNPS: A non-point-source pollution model for evaluating agricultural watersheds. *J. Soil & Water Cons.* 44(2): 168-173.

Zhang, H., C. T. Haan, and D. L. Nofziger. 1990. Hydrologic modeling with GIS: An overview. *Applied Engineering in Agriculture* 6(4): 453-458.