NONPOINT-POLLUTION MODEL SENSITIVITY TO GRID-CELL SIZE

Baxter E. Vieux   Scott Needham

1993

Journal Article   WWRC-93-06

In

Journal of Water Resources Planning and Management

Baxter E. Vieux
School of Civil Engineering
and Environmental Science
University of Oklahoma
Norman, Oklahoma

Scott E. Needham
Wyoming Water Resources Center
University of Wyoming
Laramie, Wyoming

simulation and analysis. First, the newly emergent geographic information system technology has been further extended to provide spatial data handling (input, georeferencing, and analysis) for hydrologic modeling for land-use management. Second, the GIS discretization referencing allows for convenient integration of a comprehensive surface-water, ET, and ground-water model. This facilitates a more comprehensive modeling evaluation of hydrologic impacts associated with land-use changes than was previously cost-effective. What would have taken many months of effort in terms of model parameter definition previously, can now be accomplished in several hours using digital data and the GIS.

Appendix. References

Drainage manual volume 2A—Procedures. (1991). State of Florida Dept. of Transp., Drainage Design Office, Tallahassee, Fla.

Johnson, R. C., Imhoff, J. C., and Davis, H. H. (1980). "User's manual of the hydrologic simulation program–Fortran (HSPF)." *EPA-600/9/80-015*, U.S. Envir. Protection Agency, Athens, Ga.

McDonald, M., and Harbaugh, A. W. (1988). "A modular three-dimensional finite difference groundwater flow model." *USGS Publications in Techniques of Water-Resources Investigation, TWI 6-A1*, U.S. Geological Survey, Reston, Va.

Powers, R. M., Davis, P. R., and Ross, M. A. (1989). "Modeling the hydrologic impacts of phosphate mining and reclamation in central Florida." *Proc. of ASCE Conf. on Water Laws and Management*, F. Davis, ed., ASCE, New York, N.Y.

Ross, M. A., and Ross, B. E. (1989). "Development of an integrated GIS/hydrologic model on a 386 microcomputer for reclamation design." *Proc. of ASCE Microcomputers in Civil Engineering Conf.*, ASCE, New York, N.Y.

User guide to the spatial analysis system—SPANS. (1988). Tydac Tech., Inc., Arlington, Va.

"Volume 1: Documentation, FIPR hydrological model." (1992). *FIPR Project No. 88-03-085*, Florida Inst. of Phosphate Res. (FIPR), Bartow, Fla.

Nonpoint-Pollution Model Sensitivity to Grid-Cell Size

By Baxter E. Vieux,[1] Member, ASCE, and Scott Needham[2]

Abstract: Nonpoint-pollution models estimate loadings of chemicals, sediment, and nutrients that degrade water quality. Before controls can be implemented, location and severity of pollution must be identified in the watershed basin. Geographic information systems (GISs) are computer-automated, data management systems simplifying the input, organization, analysis, and mapping of spatial information. Because nonpoint-pollution models simulate distributed watershed basin processes, a heterogeneous and complex land surface must be divided into computational elements such as grid cells. Model parameters can be derived from each grid cell directly from maps using GIS. Cell size selection, if arbitrarily determined though, yields ambiguous if not erroneous results. This paper investigates the effects of cell size selection through a sensitivity analysis of input parameters for the nonpoint-pollution model, Agricultural Nonpoint Source Pollution Model (AGNPS), using a GIS for a small research watershed. Model grid-cell sizes were found to be the most important factor affecting sediment yield. As the grid-cell sizes increase, stream meanders are short-circuited. The shortened stream lengths cause sediment yield to increase by as much as 32%.

Introduction

National efforts addressing nonpoint pollution include the Clean Water Act (CWA) Section 319, 1987, and more recently, the Reauthorization Amendments, 1990 of the Coastal Zone Management Act (CZMA) of 1972. Proposed guidance for the CZMA (*Coastal* 1991) suggests that states implement management practices for each category of land use that individually or cumulatively contribute to a degradation of coastal waters. Further, management measures that are economically achievable for the control of pollutants must have quantitative estimates of the pollution reduction effects and costs of these measures. Thus, the role of models and monitoring is to estimate the success of reducing pollution loads and improving water quality. Using the most current land-use information, the land area in the watershed that threatens a water body must be identified (*Coastal* 1991). Because nonpoint-pollution control cannot begin until location, severity, and downstream effects are identified, geographic information systems (GIS) and nonpoint-pollution models are becoming an integral part of national and state efforts to control degradation of water bodies.

Predicting impacts of nonpoint sources must include many factors because land management, topography, vegetative cover, soils, and climate affect the boundary conditions, fate, and transport of chemicals, nutrients, and sediment by surface runoff. These factors are complex and efforts to model them deterministically are possible only in small, controlled experiments where all parameters that affect the process are measured or controlled.

[1]Asst. Prof., School of Civ. Engrg. and Envir. Sci., Univ. of Oklahoma, 202 W. Boyd St., Room 301, Norman, OK 73019.

[2]Asst. Prof., Wyoming Water Res. Ctr., P.O. Box 3057, Univ. of Wyoming, Laramie, WY 82071.

Note. Discussion open until August 1, 1993. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on January 29, 1992. This paper is part of the ***Journal of Water Resources Planning and Management***, Vol. 119, No. 2, March/April, 1993. ©ASCE, ISSN 0733-9496/93/0002-0141/$1.00 + $.15 per page. Paper No. 2301.

Many simplified water-quality models replace the deterministic equations such as conservation of mass and momentum with functionally equivalent or empirical equations. However, due to simplifications, errors may propagate in the model output. These simplified models assess relative impacts of management practices rather than attempting to predict exact results. Because such models are simplified, there may be no inherent guidelines as to computational element size. The following sections first present some models that are used in identifying location and severity of nonpoint pollution: the application of GIS to collect, analyze, and display input and output of hydrologic and nonpoint-pollution modeling; and the effects of grid-cell selection on model output.

The capabilities of the GIS and the distributed process watershed model, AGNPS are exploited in this paper to investigate and show the potentially deleterious effects of cell size selection (computational element) on modeling nonpoint pollution. An exhaustive statistical analysis of effects of cell size is beyond the scope of this paper. Instead, we will consider the sensitivity of the model to parameter variation caused by changes in cell size. The scope of this paper is to: (1) Show a method of integrating a GIS and a water-quality model; and (2) show that cell size selection is not arbitrary and should be based on the spatial variability of the watershed.

The issue of cell size selection is often ignored in relation to how it affects model results and consequent decisions in locating and controlling nonpoint pollution. Many state and federal agencies involved in nonpoint-pollution control often indiscriminately use grid-cell sizes that are determined from a manpower, data-base resolution, data storage, or time constraints rather than from any consideration of the grid-cell size inherent to the spatially variable data or model computational algorithm. In our application, the GIS is used to extract and compile grid-cell data and input parameters at successively larger cell sizes for input to AGNPS. The aim of the study presented herein is to shed some light on the effects of cell size resolution on nonpoint-pollution modeling.

BACKGROUND

Nonpoint Models

Nonpoint models that address agricultural pollution sources range from statistically derived loading factors and delivery ratios to more complex models. Examples of field-scale water-quality models are CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) (Knisel 1980), ACTMO (Agricultural Chemical Transport Model) (Free et al. 1975), Hydrologic Simulation Program Fortran (HSPF) (Barnwell and Johanson 1981), and Nonpoint Simulation Model (NPS) (Donigian and Crawford 1976) and CNS. Watershed-scale nonpoint models have not been as widely developed as field-scale models. However, two models for nonpoint pollution distributed throughout a watershed basin are Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS) (Beasley et al. 1980) and Agricultural Nonpoint Source Pollution Model (AGNPS) (Young et al. 1987). Both of these models use a grid-cell data structure to represent conditions throughout the watershed. The model is lumped at the computation-element scale (grid cell) but distributed at the watershed scale.

Hession and Shalholtz (1988) describe the application of a raster-based GIS data base coupled with the Unified Soil Loss Equation (USLE) and a sediment delivery ratio to assess potential sediment loading to streams and rivers tributary to the Chesapeake Bay. This system identifies fields or

parcels that have the greatest potential to deliver sediment to water bodies. Sediment is not routed beyond the edge of field that makes the sediment delivery ratio uncertain in predicting downstream impacts. The information system is compiled at a 16-ha cell resolution covering most of Virginia.

The distributed process model, AGNPS, calculates runoff, erosion, and chemical loss generated within each grid cell. The model then routes the water, sediment, and chemical constituents downslope from one cell to the next until reaching the watershed outlet. Sediment and attached phosphorus may be deposited or transported to the next cell depending upon hydrologic characteristics for each cell. Thus, the model applicability extends beyond the edge of field to the watershed basin scale.

In choosing a particular model, complexity, data requirements, and computer hardware needs should be balanced with ease of use and model output usefulness. Model usefulness should justify the data requirements, i.e., can we gather the necessary input parameters and will the output tell us what we need to know? Further, a model should efficiently utilize the information contained in the input data. Those models that make the greatest use of GIS are distributed process watershed models (Vieux et al. 1989). These models require the division of a heterogeneous and complex land surface into a grid-cell structure. By attaching attributes (model parameters) to each soil type, land use/cover, and topography, model parameters can be derived for each grid cell directly from maps using GIS.

Areal weighting of parameters is necessary when model computational elements are larger than the polygons delineating soils or land use/cover. Areal averaging can be done quite easily using GIS, whereas manual areal averaging methods are laborious and rarely done. Uncertainty occurs because small inclusions of soils may not be mapped and parameters may be more variable. This is inherent to all modeling that lumps the parameters at some scale below which the spatial variation is not known and is not a criticism specific to the use of GIS but to models in general.

Geographic Information Systems

A GIS is a computer-automated spatial data management software that simplifies the input, organization, analysis, and mapping of large sets of complex georeferenced information. GIS may be used to build model input data sets as well as to view and manipulate model output. A GIS can also help to investigate spatial relationships between model input and output.

Considering the many spatially distributed parameters affecting nonpoint pollution, a GIS can handle voluminous input and output data, though not without some disadvantages. The efficiency of a GIS is realized if the same spatial information is utilized repeatedly. If the spatial information is used only once, then the advantages of the system probably do not justify the labor necessary to digitize the data and to build and maintain the data base. The following are some applications of GIS to water quality and/or quantity modeling.

Grayman (1975) presented the results of an environmental management computer system applied to water-quality planning for the James River Basin, Va. The Areal Design and Planning Tool (ADAPT) modeled not only wastewater treatment discharges but also the waterborne wastes from land development and nonpoint source pollution. The spatial data management and the mathematical modeling were linked together to form an integrated system that helped determine least-cost alternatives for wastewater treatment plants that met water-quality goals. The system used a

Triangular Irregular Network (TIN) data structure for both the spatial data and model. Grayman et al. (1982) applied ADAPT to urban runoff analysis demonstrating the cost-effectiveness of automated spatial data analysis. Their recommendations included that runoff models should be developed that more fully take advantage of the spatial data.

One of the earlier uses of a raster GIS data management tool for river-basin planning was described by Gupta and Solomon (1977). The GIS was used to model distributed hydrologic processes. In their application, sediment and water was modeled at the river-basin scale. The model data structure used grid cells that were the same size as the GIS grid cells. The U.S. Army Corps of Engineers have developed spatial analysis software for managing input data for the HEC1 lumped watershed model ("Variable" 1977). HEC1 belongs to the class of models that lumps parameters by subbasin in a watershed destroying the spatial variability of the data. While much effort has been applied to development by the Corps of spatial data management techniques, distributed modeling using HEC1 is not possible and, therefore, not considered further.

More recently, efforts have been toward development of models that more fully utilize the spatial data without lumping. Needham and Vieux (1989) presented the application of a vector-based GIS, ARC/INFO used to generate AGNPS input files and to display model output for a small watershed in Michigan. This method allowed areal averaging of input parameters for AGNPS and viewing the results. This method is the same method used in the study presented herein and will be described in more detail in following sections.

Vieux (1991) reviewed the applications of GIS in modeling water quality and quantity and presented an application section where finite elements were used to simulate direct surface runoff. A Triangular Irregular Network (TIN) supplied nodal land surface slopes to the finite element model. The distributed flow depths were then draped over the terrain model illustrating the capability of GIS to display distributed model results. The finite element model required spatial information that was supplied by the GIS. Thus, the model utilizes the spatial data without lumping.

Vieux (1993) found that when aggregating cells and resampling in a digital elevation model (DEM), flow-path length decreased due to meander short-circuiting by large cell sizes. Finite element simulations of direct surface runoff measured the impacts of aggregation (resampling of raster cells at larger sizes). As cell sizes increased from 30 m to 210 m, the log error increased in linear proportion to the log information content lost. Information content was measured using entropy as a measure of the spatial variability of elevation and slope. The error also linearly decreased with increasing rainfall excess intensities. As the watershed approaches equilibrium, i.e., rainfall excess rate equals outflow, the spatial heterogeneity no longer affects the hydrograph shape. Similar effects were found when smoothing algorithms were applied to the DEM and slopes subsequently derived for modeling. While it may be obvious that cell size affects the model results, practicable methods for assessing the error propagated by preprocessing of the data has not been available. The method presented by Vieux (1993) provides a means of assessing the error due to loss of spatial variability as measured by entropy loss.

METHODOLOGY

The GIS used in this study was Arc/Info (*PC* 1988), though other raster- or vector-based GIS systems could be used to similar effect. We concentrate on the vector-based capabilities because of the ability to create data sets of input parameters for AGNPS from the digitized polygons of land use (Fig. 1), soils (Fig. 2), and topography at various model cell size resolutions.

The model parameter data base was compiled for grid-cell sizes of 1-, 2-,

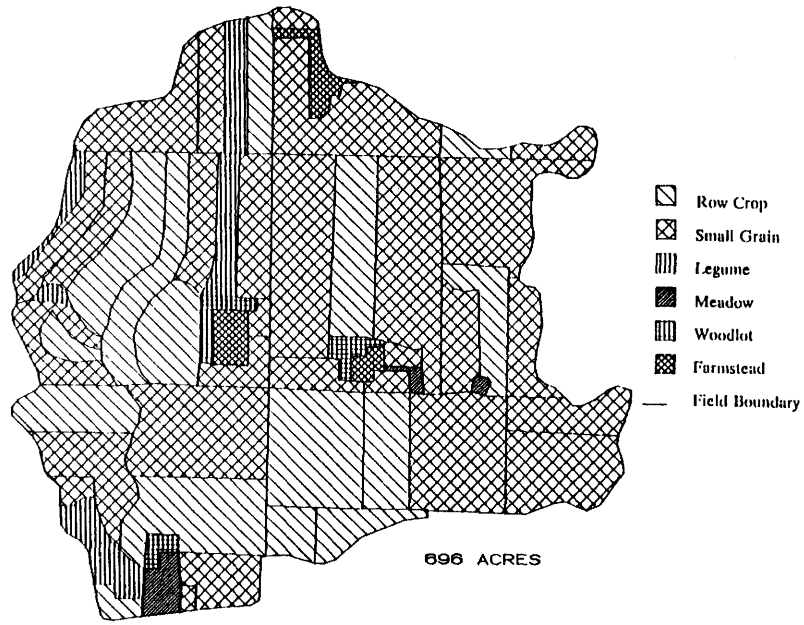

FIG. 1. Land-Use/Cover and Field Boundaries in Watershed Basin

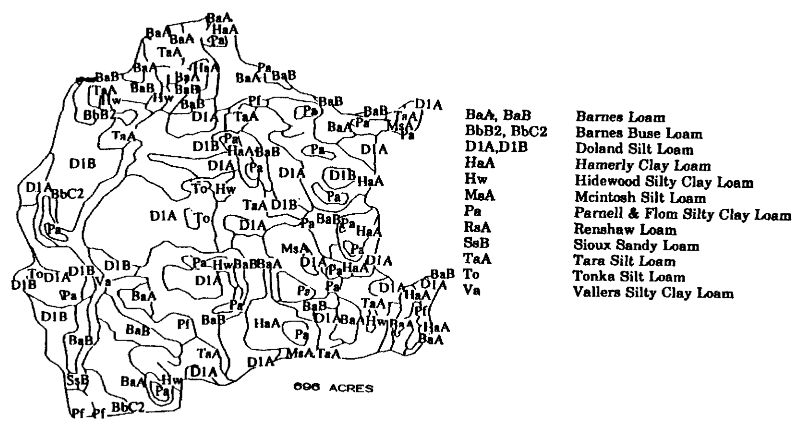

FIG. 2. Soil Coverage and Mapping Units for Watershed Basin

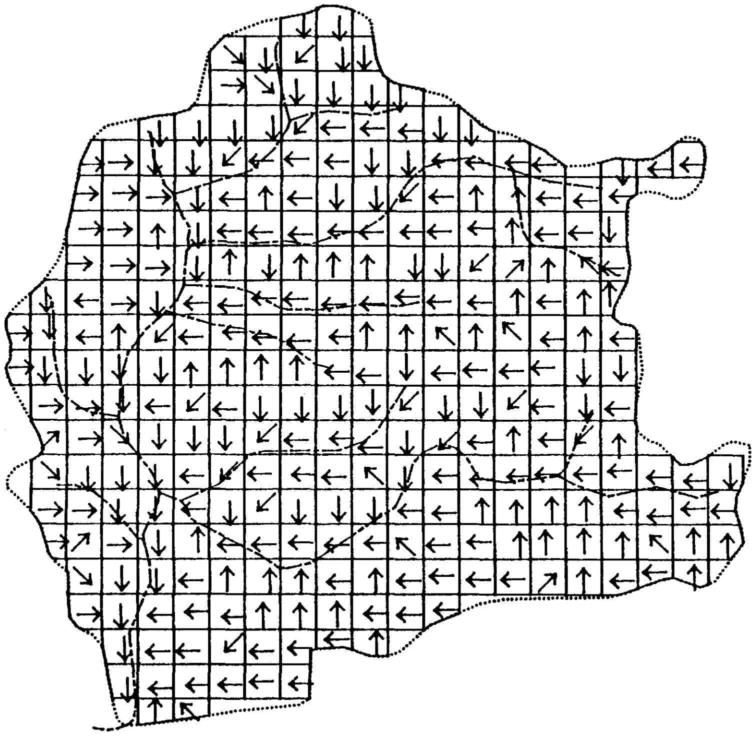

FIG. 3. Hydrography and Cell Aspects for 1-ha Cell Size

4-, 8-, 12-, and 16-ha resolution and are shown in Figs. 3–8 (1 acre = 0.4 ha). The only parameters that varied were those that were spatially dependent, management practices were invariant with respect to resolution. AGNPS was run for each of the six data sets to investigate the effects of grid-cell resolution. The storm used in the simulation was the 25-year, 24-hour storm (11.2 cm).

Study Watershed

The study watershed is an AGW7, a 282-ha watershed operated by the U.S. Department of Agriculture Agricultural Research Service, Morris, Minn. The land use in the watershed is predominantly agricultural with some forested land. Digitized soils, land use/cover, and topography for the watershed were used to build the AGNPS input parameter data base. Topography was digitized from U.S. Geological Survey (USGS) 7 1/2 min quadrangle sheets at a scale of 1:24,000. Soils were digitized from a detailed map prepared for research purposes at a scale of 1:15,840. The land-use/cover maps were developed from aerial photography and field mapping. The model parameters that must be compiled for each grid cell are given as:

1. Cell number
2. Receiving cell

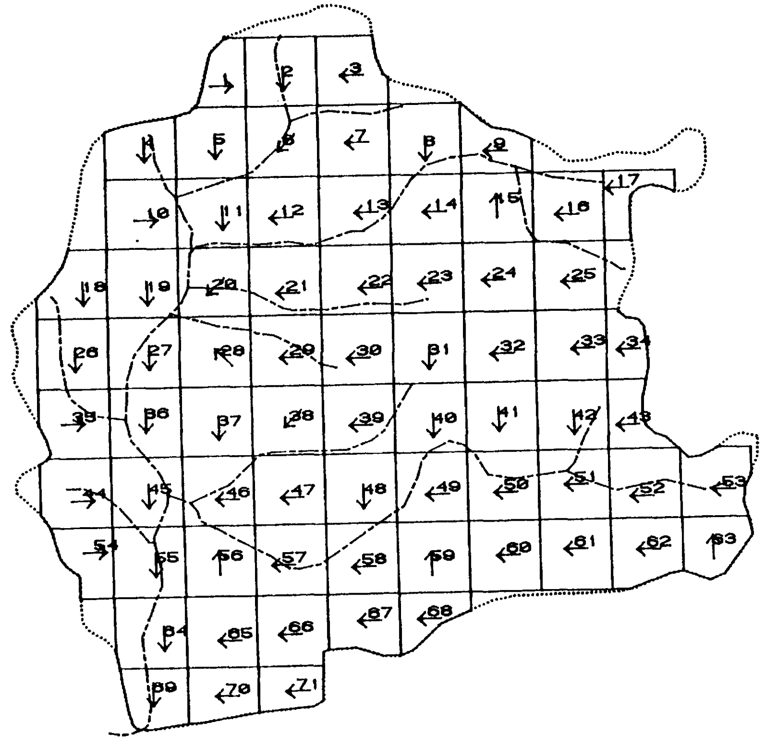

FIG. 4. Hydrography and Cell Aspects for 4-ha Cell Size

3. Aspect
4. Cover type (CN)
5. Soil hydrologic group
6. Slope
7. Slope shape
8. Field slope length
9. Manning *n*
10. *K* factor
11. *C* factor
12. *P* factor
13. Soil condition constant
14. Soil texture
15. Fertilizer amount
16. Fertilizer incorporation (percent)
17. Point source indicator
18. Gully erosion amount
19. Chemical oxygen demand (COD)
20. Impoundment factor
21. Channel indicator
22. Channel slope
23. Channel side slope

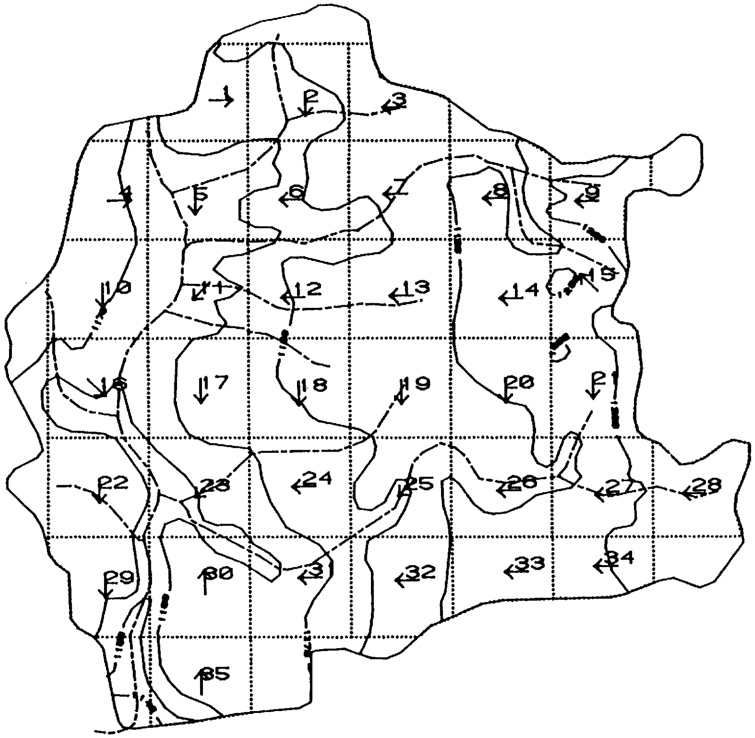

FIG. 5. Hydrography and Cell Aspects for 8-ha Cell Size

Many of the factors listed are not necessarily related to any of the spatial information contained in the digitized data base. We consider groups of parameters as they relate to the availability within the spatial data base. The numbers in parentheses correspond to the aforementioned AGNPS parameter number. A short description of each parameter follows as it relates to model parameter extraction using GIS.

Topography

The topography affects the flow directions assigned among the cells forming the drainage network. Each cell is assigned a unique identifying cell number (1) which is then used as the receiving cell (2) number by other cells. This may be done by considering the drainage network digitized as hydrography or by considering the average aspect of each cell. Aspect (3), which is classified in eight directions (neighboring cells including diagonals), affects the flow-path length across a cell and is used in routing sediment across the cell. A unique slope direction and magnitude within a single grid cell must be assigned avoiding ambiguous flow directions. Slope (6) is derivable from digitized elevation contours by overlaying the grid-cell coverage onto the TIN representing the land surface, areally averaging the slope magnitudes, and extracting the slope for each AGNPS grid cell.

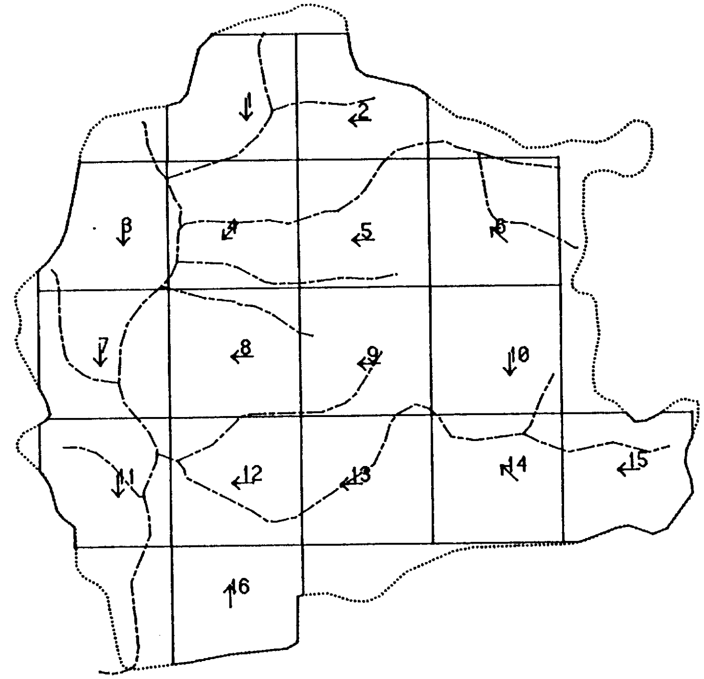

FIG. 6. Hydrography and Cell Aspects for 16-ha Cell Size

Soils

The parameters most closely related to soils are the soil hydrologic group (5), used to calculate the SCS runoff curve number; USLE *K* (10) factor, which indicates erodibility; and soil texture (14). Each of these parameters can be derived from the digitized soil maps by recoding each soil such that the soil name is replaced by its *K*-value.

Land Use

The land-use classification schemes are often not sufficiently detailed for nonpoint-pollution modeling. Depending on the classification detail model, parameters may not be identifiable for a particular land-use category. Model parameters that are closely related to land use/cover are the cover type (4), hydraulic roughness Manning *n* (9), and COD (19).

Field Investigation

Some factors can only be found through field investigation. These factors, such as slope shape (7), which identifies concavity or convexity; point source indicators (17), which allow the addition of known point sources to a cell; gully erosion amount (18); impoundment factor (20); channel slope (22); and channel side slope (23), are best determined in the field. While unlikely, aerial photography or other sources may offer some of this information. As with other parameters, these sources should be field-checked.

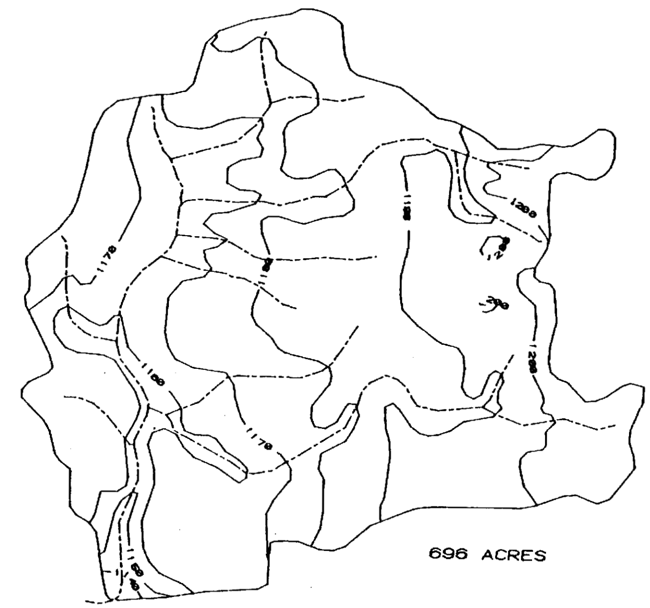

FIG. 7. Elevation Contours (ft msl) Overlayed with Hydrography

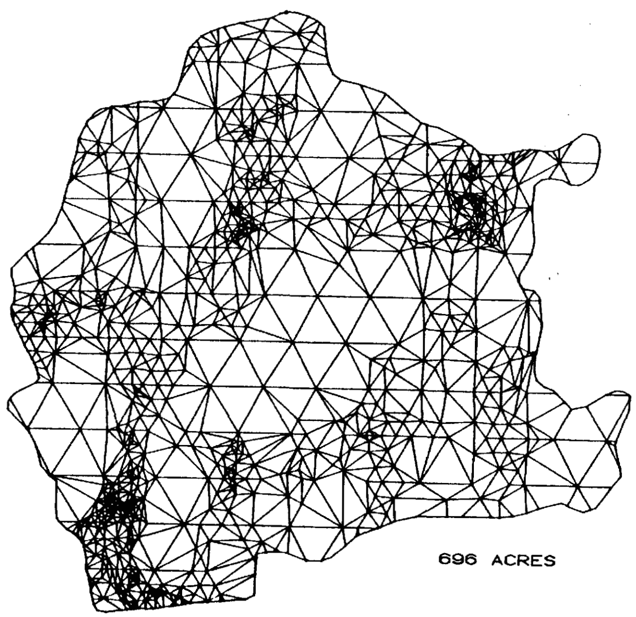

FIG. 8. TIN Derived from Digitized Elevation Contours

Management

The USLE cropping factor, *C* (11); USLE practice factor, *P* (12); the fertilizer amount (15), and incorporation percent (16) are related to agricultural management practices, and, hence, are available only through interviews with farmers in the watershed. However, reasonable factors can be assigned representing baseline conditions or a planning scenario.

Model Parameter Data Base

Attributes describe what a point, line, or polygon map feature is. Many different attributes may be associated with a single map feature. Traditionally, geographers or cartographers would consider a map feature such as a soil mapping unit to be simply the name of the soil. The innovative feature of GIS–model integration is that the attribute may be a model parameter. Thus, the task amounts to developing a data base wherein each map feature may have several attributes that are the model parameters. GIS allows linkage between tabular attribute data and the spatial data.

Fig. 1 shows the land-use classification and coverage for the watershed basin. Cover type (4), Manning *n* (9), and COD (19) were derived from this coverage. Soil hydrologic group (5), *K* factor (10), and soil texture (14) were derived from the soil coverage shown in Fig. 2.

Slope (6) may be derived by overlaying the grid-cell coverage onto the TIN coverage. Each TIN facet has a unique slope direction and magnitude. AGNPS requires a single slope magnitude. The procedure used to derive the grid-cell slope requires areal averaging of the slope magnitudes for each TIN facet. The resulting average slope magnitude becomes the grid-cell slope. Channel slope (22) was determined by overlaying digitized streams and drains onto the TIN facets and calculating average slope from the intersected TIN facets. Channel side slope (23) and slope shape (7) are assigned global default values based on general field observations. Sensitivity analyses have shown that these parameters have little influence on model output (Young et al. 1987). Considerable field time or GIS extraction is not justified for these input values.

Remaining parameters were calculated or defined as default values. It should be noted that because of the flatness of the terrain and the representation of the land surface by the TIN, the receiving cell (2) and aspect (3) were not derived using GIS but by manual methods. The grid-cell map was simply overlaid on top of the elevation contours and the dominant flow direction assigned to the cell in order to determine receiving cells. While this could be automated, the writers have found ambiguous results when using the TIN representation of topography to derive receiving cell (2) and aspect (3). The ambiguity is due primarily to the difference between grid cell and TIN data structures.

Results

Effects of Grid-Cell Size

AGNPS specifies that only those cells that have 50% or more of the area in the watershed should be used. Therefore, all cells having less than 50% are deleted using logical commands in the data-base manager. Even though partial cells are shown along the watershed, these cells fully contribute. Watershed basin area varies in size as different cell sizes are selected to represent the irregular boundary. The basin area is a multiple of the grid-cell size.

Figs. 3 through 6 show the hydrography and cell aspects of the 1-, 2-, 4-, 8-, 12-, and 16-ha cell sizes. Comparison of the drainage network between cell sizes is difficult. However, it is apparent that as cell size increases, the stream length decreases. Fig. 3 compared to Fig. 6 indicates that the stream network is short-circuited. This indicates that error may be introduced by short-circuiting flow paths. The longest flow-path length, 3,444 m, is at 1-ha resolution. Whereas, at 16-ha resolution, the flow-path length is 2,747 m. This shortening is due to meander short-circuiting. This stream-channel length was measured from a 1:12000 scale aerial photo and was found to be 3,109 m. The 4-ha grid cell most closely approximates the measured length to within 6.2%.

Fractal Dimension

Goodchild and Mark (1987) investigated the fractal nature of geographic phenomena. They found that the error in estimating area using grid cells is dependent on the fractal dimension. The fractal dimension of a line such as the stream channel varies between 1.0 and 2.0 depending on the locational variability. The fractal dimension of the longest stream channel in this study was found to be 1.16. This indicates that cell size selection will affect the apparent length.

Fig. 7 shows the elevation contours digitized from USGS 7 1/2 topography. The topography is rather flat and, in much of the watershed, is less than 1%. Even though topography is commonly taken from similar sources and scales, 3-m contour intervals may not represent the spatial variation inherent in natural landscapes. This is especially important in flat terrain since small errors in slope are, on a relative basis, much larger for flat slopes than for steep slopes.

Fig. 8 is the TIN derived from the digitized elevation contours. Flatter areas have fewer triangle facets; steeper areas have more. This results in an efficient storage of data unlike raster data structures that use regularly spaced grid cells of the same size to represent both variable and constant areas. However, the incongruity of TIN and grid-cell data structures causes ambiguity in assigning the aspect (3) using GIS. To choose a grid cell smaller than the smallest TIN facet to avoid this ambiguity negates any advantages that the TIN may have had. For these reasons, when using the TIN data structure to derive grid-cell input parameters such as aspect (3), caution should be exercised.

Model Results

Maps can be generated depicting levels of runoff, erosion, transport, or deposition across the watershed. But for our purposes and the scope of this investigation, we will examine outlet values. Similar results would obtain at other cell locations and therefore, outlet values suffice for comparison.

AGNPS generates values of runoff, erosion, sediment and nutrient transport, and deposition for each cell and routes to the outlet accumulating the entire watershed. This output data is written to an ASCII file that is then read into the GIS data base. Table 1 shows the AGNPS output values generated for the outlet cell under the six cell size scenarios. The most important variations with respect to cell size is the change in sediment yield. This in turn affects delivery ratio. The flow-path length is also shown indicating decreased length with increased cell size.

TABLE 1. Model Output for Various Cell Sizes

Output or input (1)	Cell Size 1.01 (ha) (2)	2.02 (ha) (3)	4.05 (ha) (4)	8.09 (ha) (5)	12.14 (ha) (6)	16.19 (ha) (7)
Runoff (cm)	5.33	5.08	5.08	5.08	5.08	4.83
Qp (m^{3}s)	15.29	14.75	14.64	15.66	15.06	15.12
Sediment yield (tons)	202	178	164	195	205	216
Areal weighted yield (tons/ha)	0.72	0.63	0.61	0.69	0.74	0.83
Upland erosion (tons/ha)	3.61	3.54	3.74	3.56	3.59	3.50
Channel erosion (tons/ha)	1.35	0.31	0.20	0	0	0
Delivery ratio	14	16	15	19	20	24
Number of cells	280	139	71	35	23	16
Basin area (ha)	1,569	1,558	1,592	1,569	1,547	1,435
Flow-path length (m)	3,444	3,389	3,302	2,914	2,787	2,747

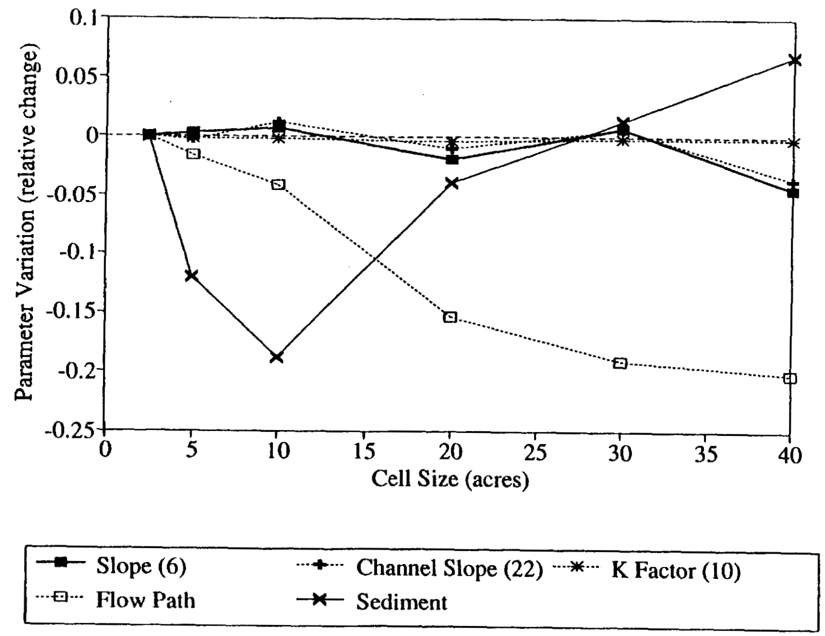

FIG. 9. AGNPS Parameter Variation versus Cell Size

Sensitivity Analysis

The sensitivity analysis reported by Young et al. (1987) showed that the parameters that most influenced sediment yield were slope (6); soil erodibility, *K* factor (10); the runoff curve numbers derived from cover type (4); and hydrologic group (5). The method used in the sensitivity analysis reported by Young et al. was to keep all other variables constant

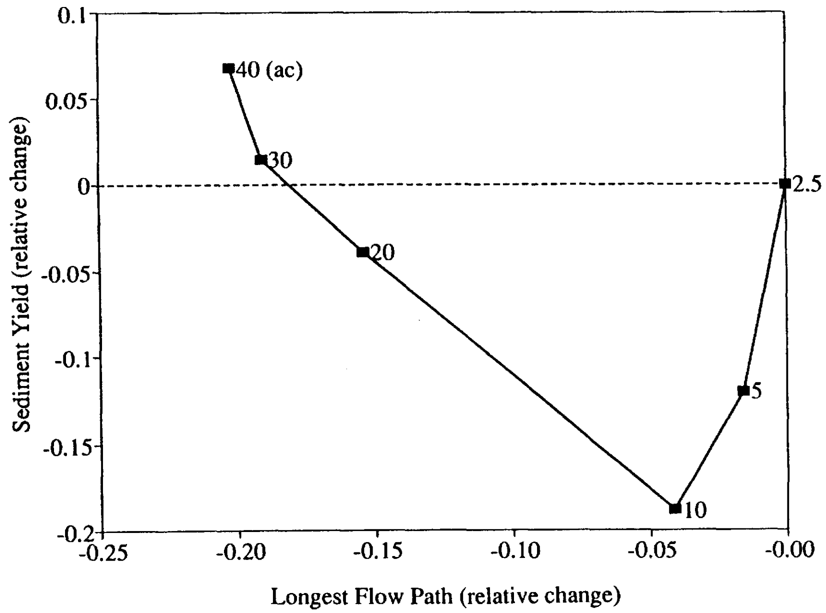

FIG. 10. Sensitivity of Sediment Yield versus Longest Flow-Path Length

while varying a parameter by ±25% and ±50% and measuring the change relative to a base value.

A similar approach is followed here except that cell size is allowed to vary causing many parameters to vary. The sensitivity of the sediment yield to the factors: slope (6); *K* factor (10), channel slope (22), and flow-path length is presented in Fig. 9. The flow-path length is not an explicit AGNPS parameter. Examination of Fig. 9 shows that the only parameters that have trends capable of accounting for the trend in sediment yield is flow-path length. The response of the flow-path length to cell size is expected since at larger cell sizes the flow path meanders are short-circuited. None of the parameters show trends that would account for the trend in sediment yield due to cell size variation. However, channel erosion is at a maximum 1.35 tons/ha at 1 ha and decreases to 0.2 tons/ha at 4 ha. At cell sizes greater than 4 ha, no channel erosion is estimated by the model.

Because the flow-path length is the only parameter exhibiting a trend with respect to cell size, it is compared to sediment yield for the range of cell sizes. Fig. 10 shows sediment yield versus the longest flow-path length on a relative change basis. Both sediment and flow-path length are normalized by the respective values at 1-ha cell size. At a cell size of 4 ha, a critical size is reached where trends reverse themselves. Even though the 1-ha cell size has the longest flow path, the channel erosion submodel causes sediment yield to be higher than at 4 ha. At cell sizes larger than 4 ha sediment yield increases. The shorter flow-path length reduces deposition and thus increases sediment transport efficiency.

Analysis

The model output values change due to changes in cell size and interaction of the various submodels. Referring to Table 1, except for sediment yield, channel erosion, and delivery ratio, most model output did not exhibit important variations. Sediment yield exhibits an interesting variation with cell size; first decreasing to its lowest value at 4 ha, then increasing at 10-ha cell sizes. Sediment delivery ratio is a measure of how efficiently the basin transports the eroded soil as sediment to the outlet. Thus, a high value indicates that more eroded soil made it to the outlet than a lower value. A low value indicates that the eroded soil was stored somewhere in the watershed by deposition. The sediment delivery ratio is often used to measure the downstream impacts of erosion control. However, the sediment delivery ratio follows a trend similar to sediment yield; first decreasing then increasing with a minimum at the 4-ha grid cell.

The 4-ha cell size appears to be a threshold or critical value below which channel erosion dominates. Because the same elevation drop must be traversed, a longer flow path should indicate flatter slopes and less sediment transport capacity. Above 4 ha, sediment supply is reduced due to the absence of channel erosion. Flow-path length continues to decrease improving sediment delivery efficiency, which is reflected in the delivery ratio (Table 1). Relative changes in sediment yield show a nearly linear increase for cell sizes of 4, 8, and 12 ha. After channel erosion is no longer present at 4 ha, the effects of shorter flow paths dominate the sediment yield and delivery ratio. Below 4 ha, the channel erosion and shorter flow paths are competing with opposite effects resulting in a delivery ratio that begins at 14, increases to 16, then decreases to 15 before beginning an increasing trend at cell sizes above 4 ha. These results are partially consistent with findings made by Feezor et al (1989) in which the best AGNPS cell size is the smallest cell size. Larger grid sizes were found to underestimate erosion when compared to smaller sizes. In the present study the smallest is not necessarily the best. The 4-ha grid cell most accurately represented the flow path. Smaller grid cells may only produce artifacts that have no physical basis. The channel length decreases with larger cell sizes suggesting a fractal dimension. Thus, the fractal model may be useful in describing the length variation due to grid-cell approximations.

Conclusions

Sediment yield is most dependent on flow-path length and, thus, estimating sediment yield without regard to cell size or other lumping effects could drastically alter the decisions made concerning nonpoint-pollution control. Further, the delivery ratio varied from 14 to 24, a 71% increase due solely to the cell size selected to represent the watershed. Delivery ratios are widely used to estimate benefits of management practices for the control of nonpoint pollution degrading downstream water quality. It is important to consider sources of error and to eliminate them when possible, especially when they are caused by arbitrary choices of cell size. It is evident that cell size affects flow-path length and model output. The best cell size may not be evident from the data. In this study, the lowest sediment yield occurred when channel erosion decreased to its lowest value, which occurred at 4 ha. The smallest cell (1 ha) size had the greatest channel erosion and the longest flow-path length (in excess of measured length). The 4-ha cell size captures the spatial variability of the watershed yielding the least sediment yield and closest flow-path length approximation.

GIS–model integration is a powerful technique in the investigation of nonpoint pollution. However, cell size selection is seldom based on the inherent spatial variability of the data. An analysis more detailed than manual methods is possible using a GIS integrated with a nonpoint source pollution model offering crucial insight into the effects of cell size. Through analyses similar to those presented herein, the effects of cell size may be investigated easily using a GIS once the supporting data is digitized. The variation of channel erosion, sediment yield, and delivery ratio due to cell size selection has been demonstrated to have important consequences when analyzing nonpoint pollution using a model such as AGNPS. Particularly, if the model results are used in economic analyses of best management practices, cell size selection may introduce unacceptable errors or erroneous conclusions.

Clearly, cell size selection is not an arbitrary choice. It should be based on the scale necessary to capture the spatial variability. Provided other parameters are accurately derived using areal averaging, the most important (though not an explicit parameter) is the stream channel approximation. The grid cell sizes should be chosen such that the flow-path lengths in the drainage network are closely approximated. The fractal dimension of the channels should be computed. If the dimension computed using the fractal model is significantly greater than 1.0, then cell size is important in capturing the length of the channel.

APPENDIX. REFERENCES

Barnwell, T. O., and Johanson, R. (1981). "HSPF: A comprehensive package for simulation of watershed hydrology and water quality." *Proc. of the Seminar on Nonpoint Pollution Control-Tools and Techniques for the Future*, Interstate Committee on the Potomac River Basin, Rockville, Md.

Beasley, D. B., Huggins, L. F., and Monke, E. J. (1980). *ANSWERS user's manual*. Purdue Univ., West Lafayette, Ind.

Coastal nonpoint pollution control program: Program development and approval guidance. (1991). U.S. Envir. Protection Agency, Washington, D.C., 22–23.

Donigian, A. S., and Crawford, N. (1976). "Nonpoint pollution from the land surface." *EPA 600/3-76/083*, U.S. Envir. Protection Agency, Washington, D.C.

Free, M. H., Onstad, C. A., and Holtan, H. N. (1975). "ACTMO: An agricultural chemical transport model." *Report No. ARS-H-3*, U.S. Dept. of Agric., Washington, D.C.

Feezor, D. R., Hirschi, M. C., and Lesikar, B. J. (1989). "Effect of cell size on AGNPS prediction." *ASAE Paper No. 89-2662*, American Society of Agric. Engrs. (ASAE), Chicago, Ill.

Goodchild, M. F., and Mark, D. M. (1987). "The fractal nature of geographic phenomena." *Ann. AAG*, 77(2), 265–278.

Grayman, W. M. (1975). "Land-based modeling system for water quality management studies." *J. Hydr. Div.*, ASCE, 101(5), 567–580.

Grayman, W. M., Males, R. M., and Harris, J. J. (1982). "Use of integrated spatial data and modeling capabilities for urban runoff analyses." *Proc. of the Int. Symp. on Urban Hydrology*, Univ. of Kentucky, Lexington, Ky.

Gupta, S. K., and Solomon, S. I. (1977). "Distributed numerical model for estimating runoff and sediment discharge of ungaged rivers. 1: The information system." *Water Resour. Res.*, 13(3), 613–618.

Hession, C. W., and Shanholtz, V. O. (1988). "A geographic information system for targeting nonpoint source agricultural pollution." *J. Soil Water Conservation*, 43(3), 264–266.

Knisel, W. G. (1980). "Creams: A field scale model for chemicals, runoff, and erosion from agricultural management systems (manual)." *USDA Conservation Res. Report Number 26*, U.S. Dept. of Agric., Washington, D.C.

Needham, S., and Vieux, B. E. (1989). "A GIS for AGNPS parameter input and output mapping." *ASAE Paper No. 89-2673*, American Society of Agric. Engrs. (ASAE), Chicago, Ill.

PC ARC/INFO users guide. (1988). Envir. Systems Res. Inst. (ESRI), Redlands, Calif.

"Variable grid resolution-issues and requirements." (1977). *Proc. of a Seminar, The Hydrologic Engineering Center*, U.S. Army Corps of Engrs., Davis, Calif.

Vieux, B. E. (1991). "Geographic information systems and nonpoint source water quality and quantity modeling." *Int. J. Hydrol. Processes*, 5(1), 101–113.

Vieux, B. E. (1993). "DEM aggregation and smoothing effects on direct surface runoff modeling." *J. Comp. Civ. Engrg.* (in press).

Vieux, B. E., Herndon, L. P., and Liston, R. (1989). "GIS and water quality modelling for agricultural resource management systems." *ASAE Paper No. 89-2184*, American Society of Agric. Engrs. (ASAE), Chicago, Ill.

Young, R. A. Onstad, C. A., Bosch, D. D., and Anderson, W. P. (1987). AGNPS, agricultural nonpoint source pollution model: A watershed analysis tool. *Conservation Res. Report 35*, U.S. Dept. of Agric. Agric. Res. Service, Morris, Minn.

Young, C. A., Onstad, C. A., Bosch, D. D., and Anderson, W. P. (1989). "AGNPS: A nonpoint source pollution model for evaluating agricultural watersheds." *J. Soil Water Conservation*, 44(2), 168–173.