A phosphorus transport model for small agricultural watersheds

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Rousseau, A., Dickinson, W. T., Rudra, R. P. and Wall, G. J. 1988. **A phosphorus transport model for small agricultural watersheds**. Can. Agric. Eng. 30: 213–220. GAMESP, the Guelph model for evaluating the effects of Agricultural Management systems on Erosion, Sedimentation and Phosphorus yields, is proposed to delineate source areas of sediment and phosphorus delivery to surface waters of small agricultural watersheds. The purpose of this study is to introduce the concepts and components of the model, describe the computational approach, and present an application of the model on a small agricultural watershed in southern Ontario.

INTRODUCTION

Phosphorus is among the major plant macronutrients applied to cropland to supplement natural fertility. Runoff from cropland areas can remove phosphorus from the land surface and transport it into surface waters. This phosphorus can be in dissolved forms (inorganic and organic phosphorus), but is mainly in particulate forms (labile, inorganic, and organic phosphorus) associated with suspended sediment detached from the land surface and carried by flowing water (Spires and Miller 1978; Nelson and Logan 1983). Consequences of phosphorus entry into surface waters can be numerous, including: (i) accelerated eutrophication of water resources, since phosphorus is a limiting nutrient in the eutrophication process (Lee 1973; Lee et al. 1978); (ii) increases in the cost of treating water supplies for municipalities and industries (Duttweiler and Nicholson 1983); and (iii) reduction of the recreational potential of water bodies.

During the past decade, phosphorus loadings from municipal, industrial, and agricultural sources have increased the level of concern regarding the eutrophication status of many water bodies of the Great Lakes Basin. Attention is now being given to the implementation of remedial strategies to reduce phosphorus loadings from agricultural sources, since phosphorus loadings from municipal and industrial sources have already been reduced by advanced wastewater treatment. Further, since phosphorus loadings from agricultural sources have been identified to be mainly associated with suspended sediment carried by cropland runoff (Miller et al. 1982; Nelson and Logan 1983); during the spring period (Alberts et al. 1978; Coote et al. 1982), it is expected that land management practices prescribed to reduce sediment loadings to surface waters will reduce phosphorus loadings to receiving water bodies (U.S. Army Corps of Engineers 1982). Moreover, since overland runoff and sediment loadings from agricultural watersheds vary spatially and temporally in the Great Lakes area (Dickinson and Whiteley 1970; Dickinson et al. 1975; Coote et al. 1982), phosphorus loadings from agricultural watersheds to surface waters are also expected to vary in space and time. Therefore, there is a need for a watershed phosphorus transport model to predict seasonal phosphorus loadings and investigate how changes in land management practices might reduce sediment-associated phosphorus loadings from cropland portions to surface waters of small agricultural watersheds.

This paper proposes the Guelph model for evaluating the effects of Agricultural Management systems on Erosion, Sedimentation, and Phosphorus yields (GAMESP), introduces the concepts and components of the model, briefly describes the computational approach of the model, and presents an application of the model on a small agricultural watershed in Southern Ontario.

CONCEPTS AND COMPONENTS OF THE GAMESP MODEL

GAMESP (Rousseau 1985) is the result of the addition of a phosphorus component to GAMES, the Guelph model for evaluating the effects of Agricultural Management systems on Erosion and Sedimentation (Cook et al. 1985; Rudra et al. 1986). The GAMESP model consists of two major components: the potential soil loss/sedimentation component, and the phosphorus component.

The conceptual approach of GAMESP involves the discretization of an agricultural watershed into land and stream cells of various sizes and shapes. Each land cell is of field size, with homogeneous characteristics of land use, soil type, and class of slope. This conceptual approach allows GAMESP to: (i) view the watershed as a system of interconnected land and stream cells, and (ii) model sediment and phosphorus transport from cropland portions to surface waters by a series of interconnected land cells delivering sediment and phosphorus loadings into a series of stream cells leading to the watershed outlet.

The potential soil loss/sedimentation component

The potential soil loss/sedimentation component of GAMESP estimates the seasonal potential soil loss for each land cell, using a seasonal application of the Universal Soil Loss Equation (Wischmeier and Smith 1978); and the subsequent seasonal amount of sediment delivered to the adjacent downstream land cell and to the downstream stream cell, using a seasonal sediment delivery ratio function (Clark 1981; Dickinson et al. 1986). On the assumption that no in-stream sedimentation process occurs, the potential soil loss/sedimentation component estimates the seasonal sediment load at the outlet of the

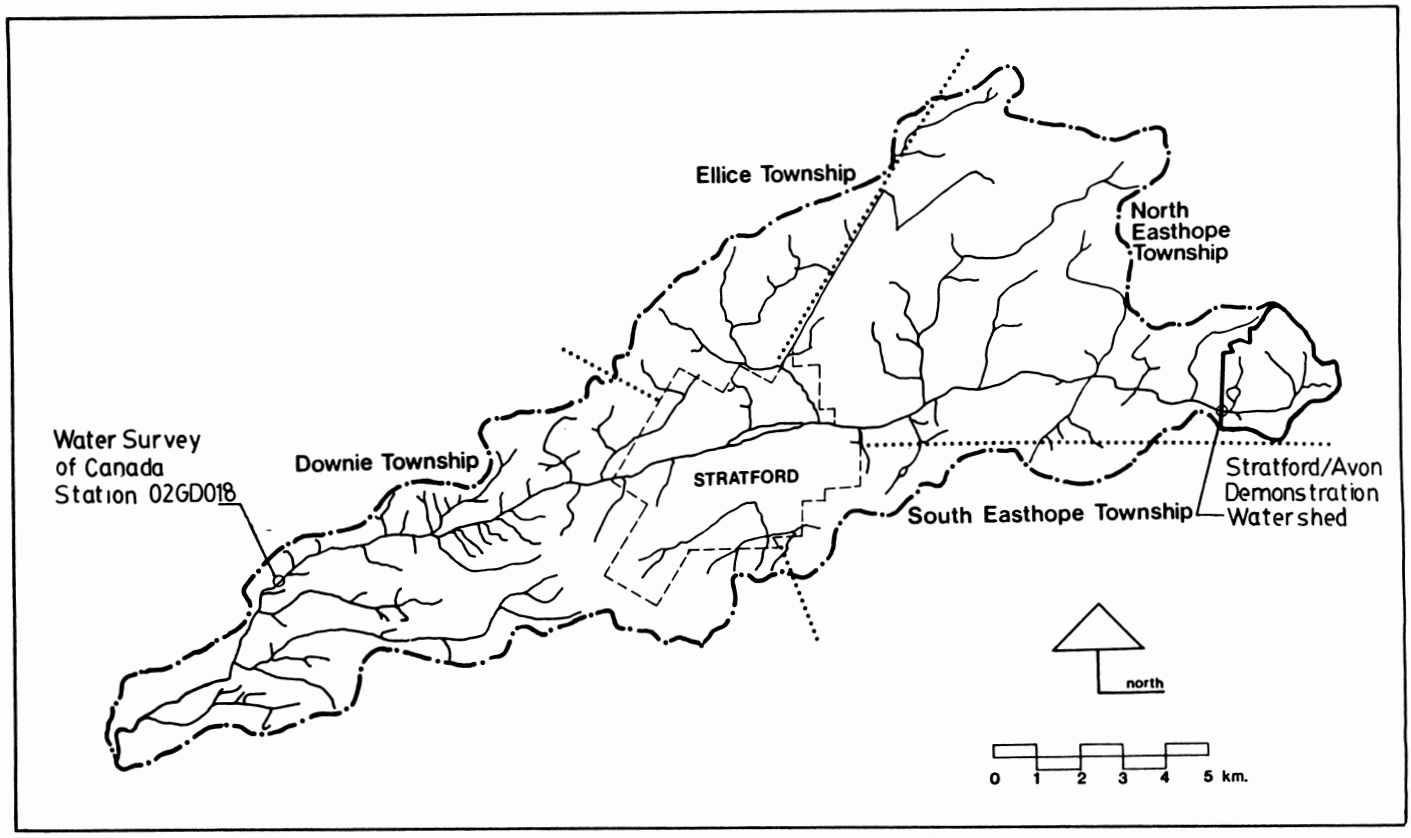

Figure 1. Location of the Stratford/Avon demonstration watershed in the Avon River Basin.

watershed by summing up all predicted cell-to-stream sediment loads.

The output from the potential soil loss/sedimentation component is a summary of the individual cell calculations for the potential soil loss, the potential soil loss rate, the cell-to-adjacent-downstream-cell sediment delivery ratio, the cell-to-adjacent-downstream-cell sediment load, the cell-to-stream sediment delivery ratio, and the cell-to-stream sediment load. It also provides an estimate of the total downstream sediment load and the average sediment load per unit area of the watershed.

The phosphorus component

Simplification of the transfer processes by which particulate and dissolved phosphorus are removed from the land surface by overland runoff has led researchers (Hagin and Amberger 1974; Spires and Miller 1978; Menzel 1980; Sharpley 1980; Nelson and Logan 1983) to predict phosphorus transport from the land surface to receiving waters by the amount of soil-derived particulate phosphorus in overland runoff, using the average total phosphorus concentration of the surface soil (10 mm), the potential soil loss, the sediment delivery ratio, and the phosphorus enrichment ratio. This concept is based on the assumption that most if not all of the phosphorus carried in overland runoff is derived from soil particles detached from the land surface by sheet and rill erosion.

The phosphorus component of GAMESP estimates for each land cell on a seasonal basis the average total phosphorus concentration of the surface soil, using a regression equation (if the average total phosphorus concentration of the surface soil is unknown), the cell-to-adjacent-downstream-cell phosphorus enrichment ratio, the cell-to-adjacent-downstream-cell phosphorus load, the cell-to-stream phosphorus enrichment ratio, and the cell-to-stream phosphorus load. The resulting seasonal phosphorus load at the outlet of the watershed is calculated by summing up all predicted cell-to-stream phosphorus loads.

The output from the phosphorus component is a summary of the individual cell calculations for the average total phosphorus concentration of the surface soil, the cell-to-adjacent-downstream-cell phosphorus enrichment ratio, sediment load, and phosphorus load and the cell-to-stream phosphorus enrichment ratio, sediment load and phosphorus load. It also provides estimates of the average and range of cell-to-stream phosphorus enrichment ratio, the downstream phosphorus load, and the average phosphorus load per unit area of the watershed.

COMPUTATIONAL APPROACH OF THE GAMESP MODEL

The potential soil loss

The University Soil Loss Equation (USLE) as presented by Wischmeier and Smith 1978), and modified for a seasonal time frame (Dickinson et al. 1984; Cook et al. 1985) is used in the potential soil loss/sedimentation component to predict seasonal potential soil loss by sheet and rill erosion on a land cell. The seasonal USLE can be written as:

$$A_s = 2.242\, R_s\, K_s\, (LS_s)\, C_s\, P_s \quad (1)$$

where:

A_s = the computed soil loss per unit area for the season under consideration (t/ha);

R_s = the seasonal rainfall and runoff factor, expressed as the rainfall erosion index for the region under consideration [hundreds of foot/ton/inch)/(acre/hour)];

K_s = the seasonal soil erodibility factor, expressed as the soil loss rate per erosion index unit for a specified soil as meas-

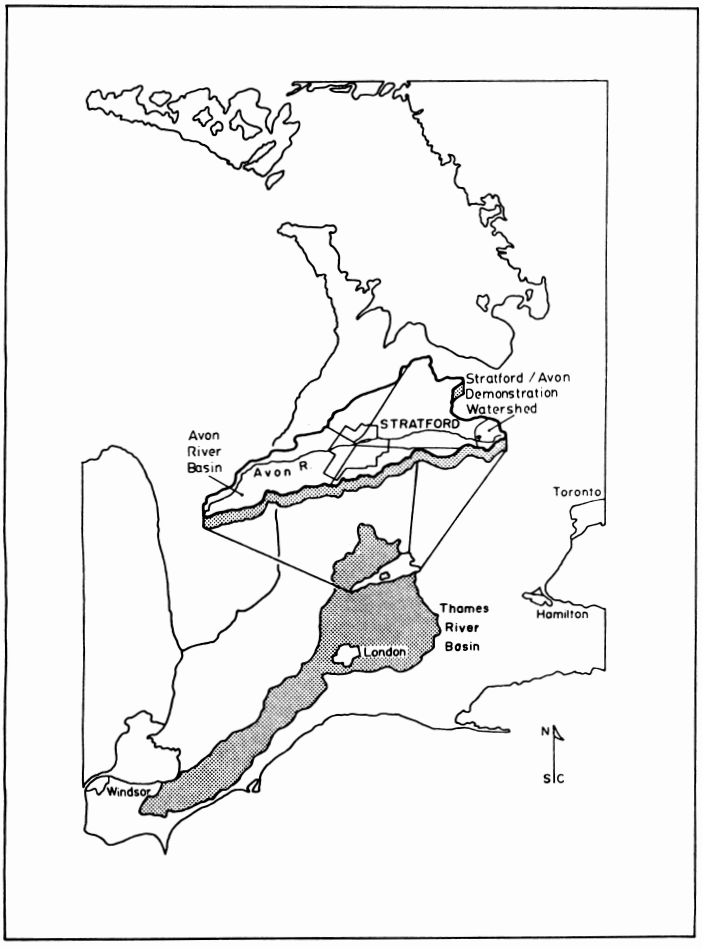

Figure 2. Location of the Stratford/Avon demonstration watershed in southwestern Ontario.

ured on a unit plot (22 m long with a 9% gradient), [ton/acre/hour)/(hundreds of acre/foot/ton/inch)];

LS_s = the seasonal topographic factor, expressed in terms of L, a slope-length factor, and S, a slope steepness factor, (ratio of soil loss from the field slope length and field slope gradient to that from a 22 m and 9% slope under identical situation);

C_s = the seasonal cover and management factor, expressed as the ratio of soil loss from an area with specified soil cover and management to that from an identical area in tilled continuous fallow;

P_s = the support practice factor, expressed as the ratio of soil loss with a support practice like contouring, to that with straight-row farming up and down the slope; and

2.242 = a conversion factor from ton/acre to t/ha.

The sediment delivery ratio

The sediment yield measured at a watershed outlet is almost never equal to the upland potential soil loss. The sediment delivery ratio has been defined as the ratio of sediment load to upland potential soil loss. The seasonal sediment delivery ratio between a land cell and a stream cell (DR) varies inversely with the travel time of overland flow from the land cell to the stream cell (Clark 1981; Dickinson et al. 1986). The sediment delivery ratio expression is a function of the surface roughness, the slope gradient, the length, and an index of the probability to generate runoff (hydrologic coefficient) on the land cells which lie in the downstream path from the land cell to the stream cell. The sediment delivery ratio expression can be written:

$$DR_s = \alpha\,(t_s)^{\beta} \tag{2}$$

where:

$$t_s = \sum_{i=1}^{m} [(1/n_{si})S_i^{1/2}Hc_{si}\,(1/L_i)] \tag{3}$$

where:

t_s = the overall seasonal time component associated with the land cell's delivery to the stream cell;

n_{si} = the seasonal Manning roughness coefficient of the ith land cell (s/m$^{1/3}$);

S_i = the slope of the flow path across the ith land cell;

Hc_{si} = the seasonal hydrologic coefficient of the ith land cell;

L_i = the length of the flow path across the ith land cell (m);

m = the number of land cells in the downslope path, including the current land cell; and

α,β = parameters of the expression.

Application of this expression to a watershed requires that the parameter values α and β be determined for that watershed. In the GAMESP model, the calibration of α and β is performed by a predetermined optimization routine (Rosenbrock and Storey 1965) which minimizes the difference between the predicted total sediment load (summation of all predicted cell-to-stream sediment loads) and the observed total sediment load at the watershed outlet. In the case where the calculated delivery ratio is greater than one, the delivery ratio is set equal to one.

The total sediment load

The seasonal total sediment load at the watershed outlet is calculated by the following expression:

$$L_s = \sum_{i=1}^{n} A_{si}DR_{si} \tag{4}$$

where:

L_s = the seasonal total sediment load at the watershed outlet (t);

A_{si} = the seasonal potential soil loss rate of cell i, (t/ha);

DR_{si} = the seasonal sediment delivery ratio of cell i to the watershed outlet (dimensionless); and

n = the number of land cells in the watershed.

The average total phosphorus concentration of the surface soil

The seasonal average total phosphorus concentration of the surface soil (10 mm) can be used as an input parameter if known, or can be estimated by a regression equation. The equation developed by Spires and Miller (1978) and proposed in the phosphorus component of the model is:

$$TP_s = 177.7 + 92.4(OM_s) + 12.9(AP_s) - 0.15(AP_s)^2 - 2.93(OM_s)^2 \tag{5}$$

where:

TP_s = the seasonal average total phosphorus concentration of the surface soil (μg/g);

OM_s = the seasonal organic matter content (%); and

AP_s = the seasonal average sodium bicarbonate ($NaHCO_3$) extractable phosphorus concentration of the surface soil as determined by the Ontario Soil Test Laboratory, Guelph, Ontario (μg/g).

This equation is valid for a range of organic matter content between 0 and 33%, and for a range of sodium bicarbonate

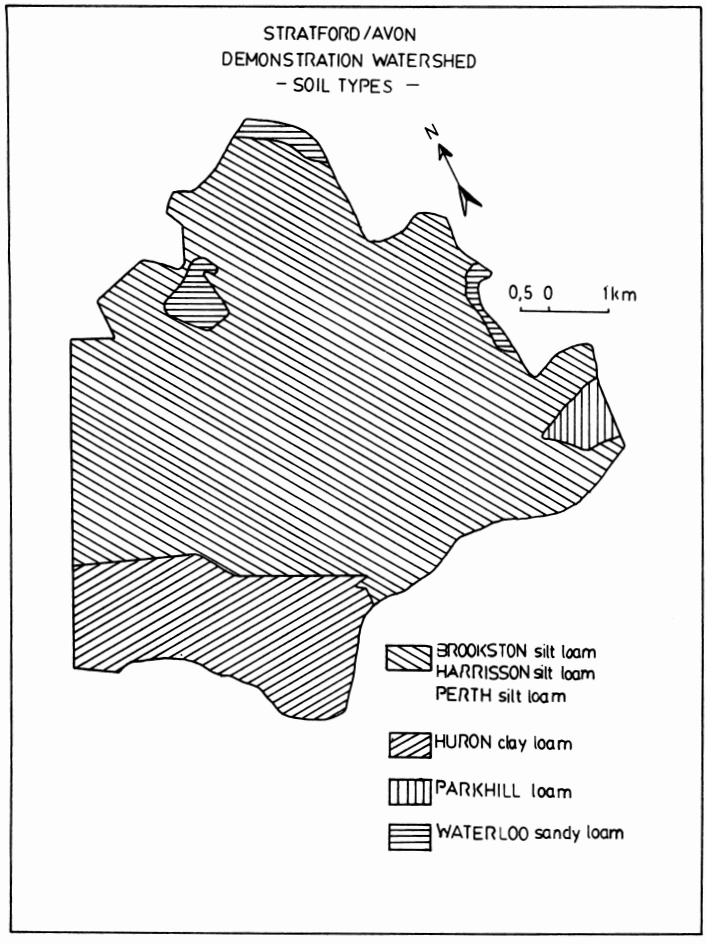

Figure 3. Spatial distribution of soil types in the Stratford/Avon demonstration watershed.

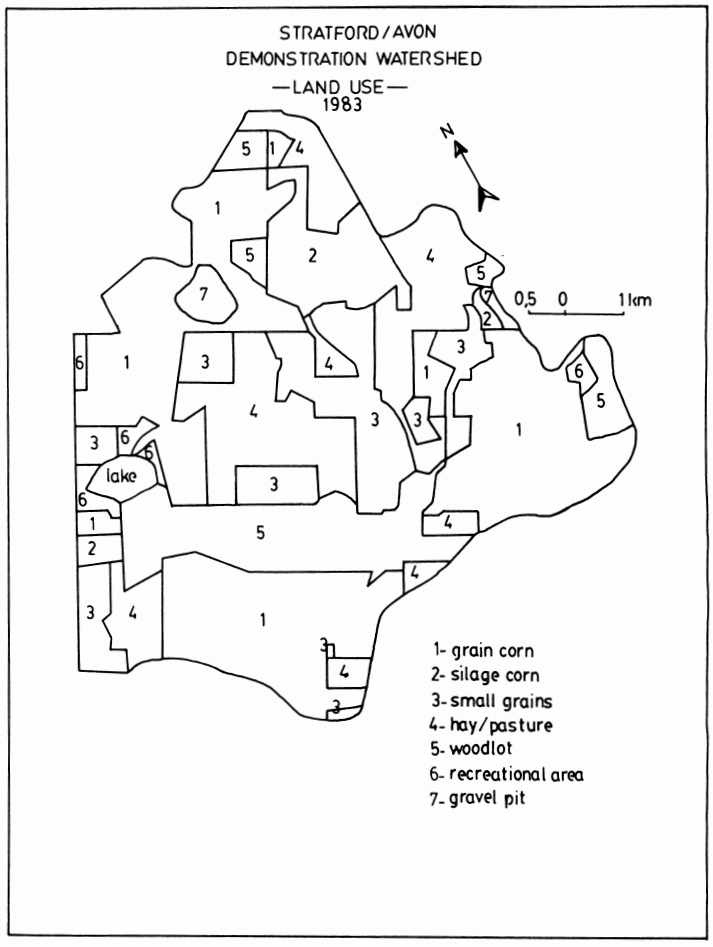

Figure 4. Land use distribution in the Stratford/Avon demonstration watershed for the 1983 crop year.

extractable phosphorus concentration of the surface soil between 0 and 88 g/g.

The phosphorus enrichment ratio

The seasonal phosphorus enrichment ratio is defined as the ratio of the concentration of phosphorus in sediments over the concentration of phosphorus in the source soil. It is used to quantify the trend that sediment-associated phosphorus in overland runoff contains higher concentrations of phosphorus than the source soil. As soil loss increases, more of the coarser particles are transported, and at some point the particle size distribution of the runoff sediments approaches that of the source soil and the phosphorus enrichment ratio approaches 1. This relationship has been expressed as a negative linear logarithmic function by Menzel (1980) and Sharpley (1980) and is proposed as a negative power logarithmic function in the phosphorus component of GAMESP. This function is used to estimate the seasonal phosphorus enrichment ratio between a land cell and the adjacent downstream land cell or a stream cell as follows:

$$PER_s = a(SED_s)^{-b} \tag{6}$$

where:

PER_s = the seasonal phosphorus enrichment ratio between a land cell and the adjacent downstream land cell or a stream cell;

SED_s = the seasonal sediment discharge rate between a land cell and the adjacent downstream land cell or a stream cell;

a,b = parameters to be calibrated.

Application of this expression to a watershed requires that the parameter values of a and b be determined for the watershed. In the GAMESP model, the calibration of parameters a and b is accomplished by an optimization routine which minimizes the difference between the predicted total phosphorus load (summation of all predicted cell-to-stream phosphorus loads) and the observed total phosphorus load at the watershed outlet. In the case where the calculated phosphorus enrichment ratio is less than one, the phosphorus enrichment ratio is set equal to one.

The total phosphorus load

The seasonal total phosphorus load at the watershed outlet is calculated by the following expression:

$$L_{ps} = \sum_{i=1}^{n} 0.001\, A_{si} DR_{si} TP_{si} PER_{si} AREA_i \tag{7}$$

where:

L_{ps} = the seasonal total phosphorus load at the watershed outlet (kg);

A_{si} = the seasonal potential soil loss rate of cell i (t/ha);

DR_{si} = the seasonal sediment delivery ratio of cell i to the watershed outlet (dimensionless);

TP_{si} = the seasonal average total phosphorus concentration of the surface soil of cell i (μg/g);

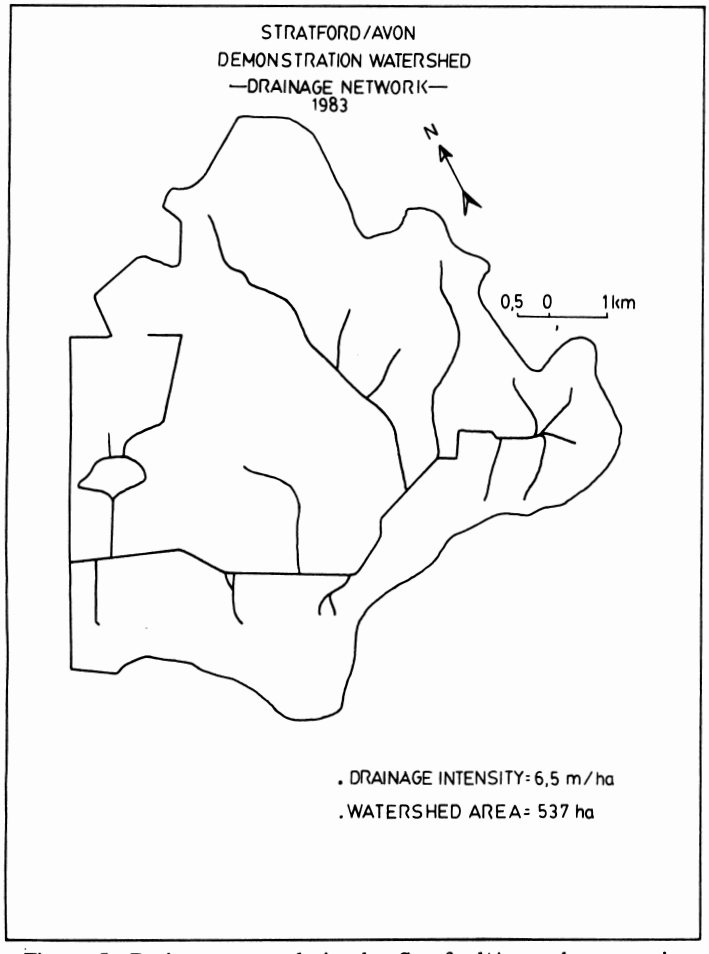

Figure 5. Drainage network in the Stratford/Avon demonstration watershed.

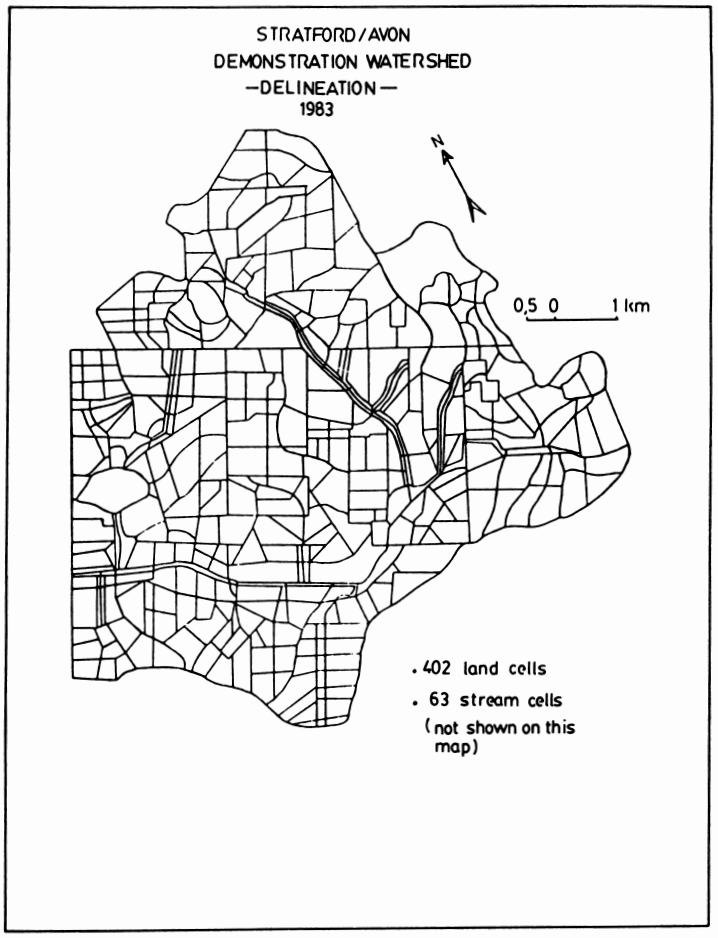

Figure 6. Discretization of the Stratford/Avon demonstration watershed.

PER_{si} = the seasonal phosphorus enrichment ratio of cell i to the watershed outlet (dimensionless),

$AREA_i$ = the area of cell i (ha); and

n = the number of land cells in the watershed,

and a conversion factor of 0.001 kg/g is applied.

APPLICATION OF THE GAMESP MODEL

Application of the GAMESP model to a study watershed involved: (i) discretization of the watershed into land and stream cells; (ii) determination of the drainage network on each cell; (iii) quantification of the input parameters required by the potential soil loss/sedimentation component and the phosphorus component for each cell; (iv) estimation of sediment and phosphorus loads at the watershed outlet attributable to sheet and rill erosion from cropland for the season under consideration; (v) calibration of parameters α and β of the sediment delivery ratio expression so that the error between predicted and observed sediment loads at the watershed outlet was minimized; and (vi) calibration of parameters a and b of the phosphorus enrichment ratio expression so that the error between predicted and observed phosphorus loads at the watershed outlet was minimized.

Sample model application

To illustrate the utility of the GAMESP model to delineate source areas of sediment and phosphorus delivery to surface waters of small agricultural watersheds, the model was applied

Table I. Input parameters for the potential soil loss/sedimentation component and the phosphorus component for the 1983 spring season

Soil type	Soil erodibility factor [(ton/acre/hour)/(hundreds of acre/foot/ton/inch)]	Organic matter content (%)
Brookston Silt Loam	0.48	4.5
Harrison Silt Loam	0.48	4.5
Perth Silt Loam	0.48	4.5
Huron Clay Loam	0.21	4.0
Parkhill Loam	0.33	3.2
Waterloo Sandy Loam	0.48	3.2

Land use	Crop and management factor (dimensionless)	Manning roughness coefficient ($s/m^{1/3}$)	Sodium-bicarbonate-extractable phosphorus (g/g)
Grain corn	0.503	0.07	21
Silage corn	0.503	0.07	21
Small grains	0.335	0.04	21
Hay/pasture	0.020	0.20	20
Woodlot	0.010	0.65	11
Recreational area	0.200	0.10	11
Gravel pits	0	0.20	11

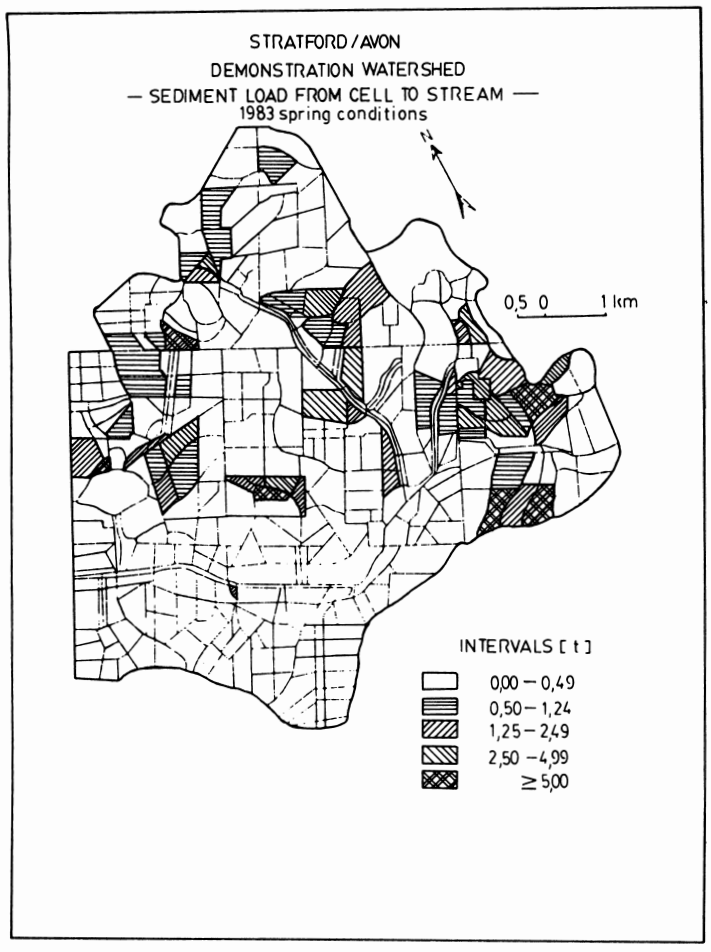

Figure 7. Spatial variability of cell-to-stream sediment yield in the Stratford/Avon demonstration watershed for the 1983 spring conditions.

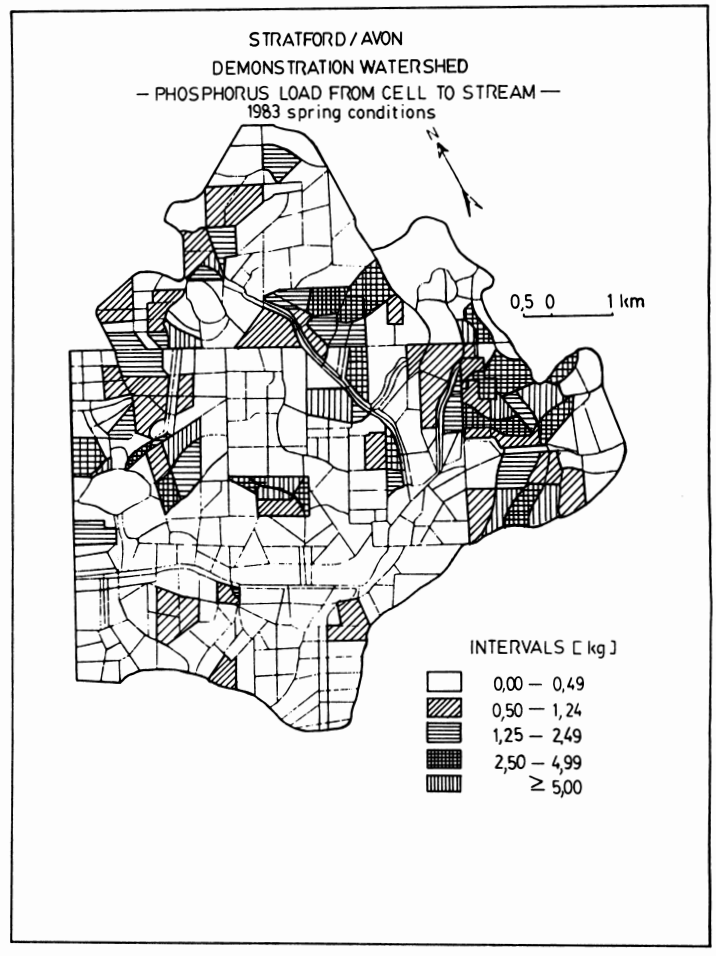

Figure 8. Spatial variability of cell-to-stream phosphorus yield in the Stratford/Avon demonstration watershed for the 1983 spring conditions.

on the Stratford/Avon Demonstration Watershed (Stratford Avon River Environmental Management Project, 1983). This watershed of 5.37 km² is located in North Easthope Township, Perth Country, within the Avon River Basin (Fig. 1), a subwatershed of the North Thames Basin in Southwestern Ontario (Fig. 2).

The principal land form of the area is the Easthope moraine in the Waterloo physiographic region, and the land is distinctly rolling. The predominant soil in the watershed is silt loam, with some clay loams, loams, and sandy loams also present. Figure 3 shows the spatial distribution of these soil types.

The agricultural activities of the area are predominantly livestock based, including swine, beef, and dairy operations. Cropping practices reflect the emphasis on livestock operations, with rotations of hay/grain/corn or hay/grain being preferred. Continuous row cropping with corn is the next most frequent system. Figure 4 represents the spatial distribution of these land uses for the 1983 crop year. An almost universal tillage practice in the watershed is fall plowing with a moldboard plow. Another fairly common practice in the fall is to either disc or cultivate prior to or following plowing. Secondary tillage in the spring usually involves two or three passes with a cultivator. The use of fertilizers in the spring season is another universal practice throughout the watershed. The average drainage density of the watershed is 6.5 m/ha (Fig. 5).

The watershed is within the Huron Slopes climatic region of Southern Ontario. The area has warm summers, mild winters, and a long growing season with usually-reliable rainfall. The effects of the Great Lakes ensure a fairly uniform seasonal distribution of precipitation along with moderating extremes of heat and cold.

Development of a watershed data base

The development of a watershed data base for the Stratford/Avon Demonstration Watershed has involved: (i) development of a composite overlay of land use, soil, topography, and drainage network maps (1:5000) to divide the watershed into homogeneous land and stream cells; (ii) determination of the drainage network on each cell; (iii) estimation for each cell of the input parameters required by the potential soil loss/sedimentation component and the phosphorus component; and (vi) estimation of sediment and phosphorus loads at the watershed outlet, attributable to sheet and rill erosion from cropland for the 1983 spring season.

The discretized watershed consists of 402 land cells, ranging in size from 0.1 to 12.1 ha, with an average of 1.3 ha; and 63 stream cells (Fig. 6). Each land cell is characterized by a single land use, a single soil type, and a single class of slope.

The input parameters for the potential soil loss/sedimentation component (the seasonal rainfall and runoff factor, the seasonal soil erodibility factor, the seasonal cover and management factor, the support practice factor, the seasonal topographic factor, the seasonal Manning roughness coefficient, and the seasonal hydrologic coefficient) have been quantified according to

Table II. Areas of the Stratford/Avon demonstration watershed exhibiting spring potential soil loss, sediment, and phosphorus yield rates and the coresponding potential soil loss, sediment phosphorus yields

Potential soil loss, sediment, and phosphorus yields rates (t/ha) or (kg/ha)	Potential soil loss				Sediment				Phosphorus			
	Area		Yield		Area		Yield		Area		Yield	
	(ha)	(%)	(t)	(%)	(ha)	(%)	(t)	(%)	(ha)	(%)	(kg)	(%)
0 – 0.49	178	33	33	1	472	88	34	21	419	78	41	16
0.50 – 1.24	65	12	55	2	30	5	24	15	64	12	49	19
1.25 – 2.49	52	10	98	4	22	4	43	26	25	5	42	16
2.50 – 4.99	72	13	250	10	9	2	30	18	23	4	79	31
5.00	170	32	2146	83	4	1	32	20	6	1	46	18

Wischmeier and Smith (1978), and Cook et al. (1985). The seasonal organic matter content and sodium bicarbonate extractable phosphorus concentration of the surface soil for the phosphorus component have been estimated from Publication 492, AGDEX 500 (Ontario Ministry of Agriculture and Food), and from the Ontario Soil Test Laboratory, Guelph, Ontario, respectively (Rousseau 1985). All the parameters (Table I) have been quantified for the 1983 spring season (February, March, April, and May).

From water discharge, sediment, and phosphorus data collected at the watershed outlet, 163 t of sediment and 257 kg of phosphorus, attributed to sheet and rill erosion from cropland, have been estimated to be delivered at the watershed outlet during the 1983 spring season (Rousseau 1985).

Model calibration

For an estimated downstream sediment load of 163 t for the 1983 spring season, the calibrated parameters and of the sediment delivery expression were 8.3 and 1.16, respectively.

Calibration of parameters *a* and *b* of the phosphorus enrichment ratio expression has been performed in two steps. Firstly, published data (Sharpley 1980) have indicated that parameter *b* is not a function of soil texture and soil phosphorus status, and parameter *a* is a function of the soil phosphorus status. This observation has prompted the use of a constant value of 0.2 for parameter *b* as suggested by Menzel (1980). Therefore, for an estimated downstream phosphorus load of 257 kg for the 1983 spring season, the calibrated parameters *a* and *b* of the phosphorus enrichment ratio expression were 9.2 and 0.2, respectively, and they were in agreement with the parameter *a* and *b* values proposed by Sharpley (1980) and Menzel (1980).

Results of the potential soil loss/sedimentation component and the phosphorus component

Calibration of the GAMESP model on the Stratford/Avon Demonstration Watershed has provided a delineation and mapping of the source areas of sediment and phosphorus yields (attributed to sheet and rill erosion) for the watershed for the 1983 spring season.

Analysis of Figs. 7 and 8 in conjunction with the results presented in Table II has prompted the following estimations: (i) 83% of the potential soil loss occurred in 32% of the watershed area; (ii) 20% of the sediment yield originated from only 1% of the watershed area; (iii) 12% of the watershed area contributed 79% of the watershed sediment yield; (iv) 18% of the watershed phosphorus yield was from only 1% of the watershed area; (v) 22% of the watershed contributed to 84% of the watershed phosphorus yield; (vi) the major portion of the watershed phosphorus yield was transported across a small percentage of the watershed area, since most of the phosphorus yield originated from steeply-sloped corn and grain fields located near the drainage channel; (vii) relatively steeply sloped corn and grain fields remote from good drainage channels exhibited serious local erosion problems but contributed little or no sediment or phosphorus yield to the stream; and (viii) the spatial variability of cell-to-stream phosphorus yield reflected the spatial variability of cell-to-stream sediment yield. Further, for the 1983 spring season, the average cell-to-stream phosphorus enrichment ratio for the watershed was 2.4.

CONCLUSION

GAMESP, the Guelph model for evaluating the effects of Agricultural Management practices on Erosion, Sedimentation, and Phosphorus yields is a useful model for the preliminary delineation and mapping of source areas of sediment and phosphorus delivery to surface waters of small agricultural watersheds. The model is based on the discretization of a watershed into land and stream cells of various sizes and shapes. The model consists of two major components: the potential soil loss/sedimentation component and the phosphorus component. GAMESP is easy to use and cost effective (designed for microcomputer application), making use of limited amounts of readily available input data and easily quantifiable physical and hydrological characteristics of the watershed. Further, since model parameters are correlated to land management practices, GAMESP exhibits considerable promise for investigating how changes in land management practices might reduce sediment-associated phosphorus loadings from cropland portions to surface waters of small agricultural watersheds. It must be noted, however, that only after extensive field validation can a model of this kind eventually become a working tool, useful as a guide in the practical management of field situations.

The GAMESP package, including disk and user's manual, is avaialble for use on IBM PC™ and compatible microcomputers. Inquiries concerning the model, its availability and its applicability should be directed to its authors.

ACKNOWLEDGMENTS

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