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Seasonally Variant Spatial Variability and Implications for Watershed Modeling, Monitoring and Management

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ABSTRACT: Many water resources issues now require careful consideration of not only the spatial variability of hydrologic processes but also the seasonal variability of the spatial variability in watersheds. Examples of such issues explored in this paper relate to the identification and management of diffuse sources of sediment contamination of surface waters in selected agricultural watersheds in North America. A description is given of what has been learned about the seasonal variability of spatial distributions of relevant flow vectors in the sample watersheds. Decisions are discussed regarding the selection and running of watershed models deemed useful for the estimation of downstream loads, and the identification of likely contaminant sources. Attention is given to the location and frequency of monitoring that is required for both the validation of models and the evaluation of impacts of remediation measures. Finally the need for a targeted approach to implementation of remedial measures—targeted both spatially and seasonally is addressed.

INTRODUCTION

During the last few decades, the change in downstream water quality due to land use activities has become an important environmental issue. Watershed scale non-point source models are being adopted for selection and evaluation of best management practices. The effectiveness of the best management practices depends upon the temporal and spatial variability of the pollution sources. In many regions around the globe the flows and sediment loads in the stream exhibit seasonal pattern. For example in southern Ontario majority (a very high percentage) of the flow and sediment in the stream occur during later winter and early spring period. In the alluvial planes of India, a significant portion of soil erosion, stream flow, and sediment occur during monsoon period. Also the magnitude and variability of soil loss and sediment loads depend upon the spatial distribution of soil, land use and topography of the watershed. Modeling approaches have become very popular for management of water resources. The nonpoint source pollution models can't be considered a replacement for comprehensive field monitoring programs; however, models have been proven to be very useful for extension and extrapolation of monitored data at locations lacking measurements. Advancement in computational technology and availability of topographic, land use, and soils data in the digital format has enhanced the application of models for nonpoint source pollution management. Models have been useful tools in identification of possible sources, magnitude, and possible pathways of pollution in the prediction of runoff quantity and quality; in selection of Best Management Practices (BMPs), remedial strategies; and in development of effective monitoring programs. This paper discusses models as watershed management tools and then highlights some of the challenges to eliminate obstacles in the application of models for watershed management. This paper also focuses on the role of seasonal and spatial variability in the modeling and management of nonpoint source pollution and monitoring programs to evaluate the effectiveness of BMPs and remedial strategies adopted for control.

STUDY APPROACH

The approach followed in this paper focuses on the management of soil erosion and fluvial sedimentation. It includes the description of the temporal and spatial variability of the watershed soil erosion and sediment loads in southern Ontario streams. The temporal distribution of sediment load has been described by the analysis of the observed flow and sediment load data. The role of the spatial variability in the topography has been quantified by analyzing the soil erosion and sediment load pattern from rolling upland and flat lowland watersheds with and without management practices. The impact of spatial variability of soil, land

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use, topography on the distribution of soil erosion and sediment yield areas, and the identification of monitoring location has also been described. The distribution of potential soil erosion and sediment loads has been estimated by application of a watershed model, GAMES (Rudra *et al.*, 1986), to two small but diverse agricultural watersheds: a rolling upland watershed (Startford Avon) and a relatively flat lowland basin (Big Creek), in southern Ontario conditions. Both watersheds were extensively studied during the PLUARG program (Wall *et al.*, 1978; Wall *et al.*, 1979), and post PLUARG program (Dickinson *et al.*, 1986a, Dickinson *et al.*, 1986b, Dickinson *et al.*, 1987; Rousseau *et al.*, 1987a; Rousseau *et al.* 1987b; Rousseau *et al.*, 1988; Dickinson *et al.*, 1990; Rudra *et al.*, 1994).

The upland watershed, 537 ha in area, has a rolling upland topography with land slopes up to 9%. The dominant soil in this watershed is loam (OMAF, 1975), and is predominantly under corn cultivation (Rousseau *et al.*, 1988; Dickinson *et al.*, 1990). During the study period (early and mid 80's) fall ploughing was common tillage practice, with few, conservation practices in place until quite recently. The lowland watershed has an area of 3300 hectares on level lowland with land slope between 0 and 2%. The predominant soil textures are clay and clay loam, (OMAF, 1975) and the land use activities are mainly limited to row crops of corn and soybeans (Rousseau *et al.*, 1988; Dickinson *et al.*, 1990). A complete data set to run the soil loss and sediment delivery components of GAMES was available for each watershed. Dickinson *et al.* (1987) used the GAMES model, developed by Rudra *et al.* (1986), to classify these watershed areas into four problem categories: area exhibiting only erosion and sediment problem, area exhibiting only erosion problem, area exhibiting only sediment problem, and the area exhibiting no problem. Dickinson *et al.* (1993) further used the GAMES model to evaluate the targeted approach to evaluate the impact of remedial strategies on these watersheds. Rudra *et al.* (1994) used the GAMES model on these watersheds to identify the location of the monitoring stations.

GAMES is a watershed scale screening model (Rudra *et al.*, 1986). In this model the watershed is discretized into irregular cells (fields). Land use, soils and land slope information are independently ascertained from available maps, aerial photographs and field surveys or GIS layers. A composite mapping of land use, soils, and land slope class is used to divide each watershed area into irregular, field-scale cells, each of which was characterized by a single land use, a single soil type, and a single class of slope. The Universal Soil Loss Equation (Wischemeier and Smith, 1978) is used to compute annual or seasonal potential soil loss from each field. The sediment load contribution by each field within the watershed is estimated by using micro delivery ratio approach (Clark, 1981 and Dickinson *et al.*, 1986a). The values of potential soil loss and sediment yield are used to describe the spatial variability of soil loss and sediment yield, soil erosion and sediment source areas, the effectiveness of BMPs, remedial strategies and development of monitoring programs.

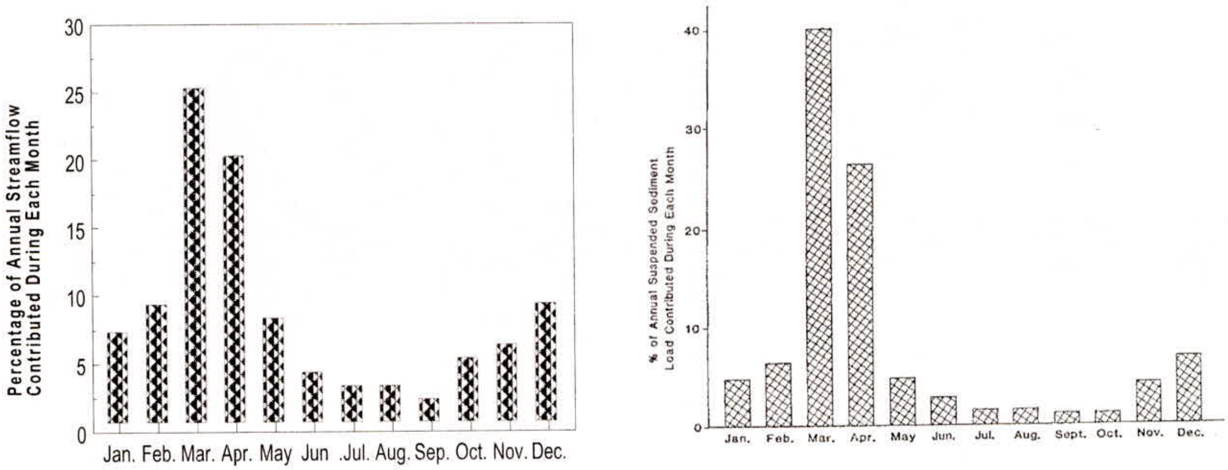
RESULTS AND DISCUSSION

Implication of Temporal Variations of Stream Flows and Sediment Loads in Nonpoint Pollution Management

Figure 1 presents monthly pattern of long-term average flow and sediment loads at the watershed outlet. These data present the long term average temporal pattern in watersheds of varying size and dominated by agricultural activities (Dickinson and Green, 1988, Water Quantity Resources of Ontario, 1984). These results indicate that maximum flows and sediment loads occur during spring months followed by fall. Four months, from February to May, contribute more than 65% of stream flow (Figure 1(a)) and more than 80% of sediment loads (Figure 1(b)). During fall months, from October to December, the maximum contribution to annual stream flow and sediment loads is less than 20% and 12%, respectively. During summer months (June, July, August, and September) the average monthly contribution to the annual stream flow and sediment loads is 3 and 2%, respectively. During these months, the area contributing to the stream flow is area of the stream (generally 2 to 3%) and the area very close to the stream banks. From these data it could be concluded that for management of sediment non-point source pollution spring is the most critical season. Therefore, to describe the implication of spatial variability on the modeling, management, and monitoring of nonpoint source requires focus on spring season.

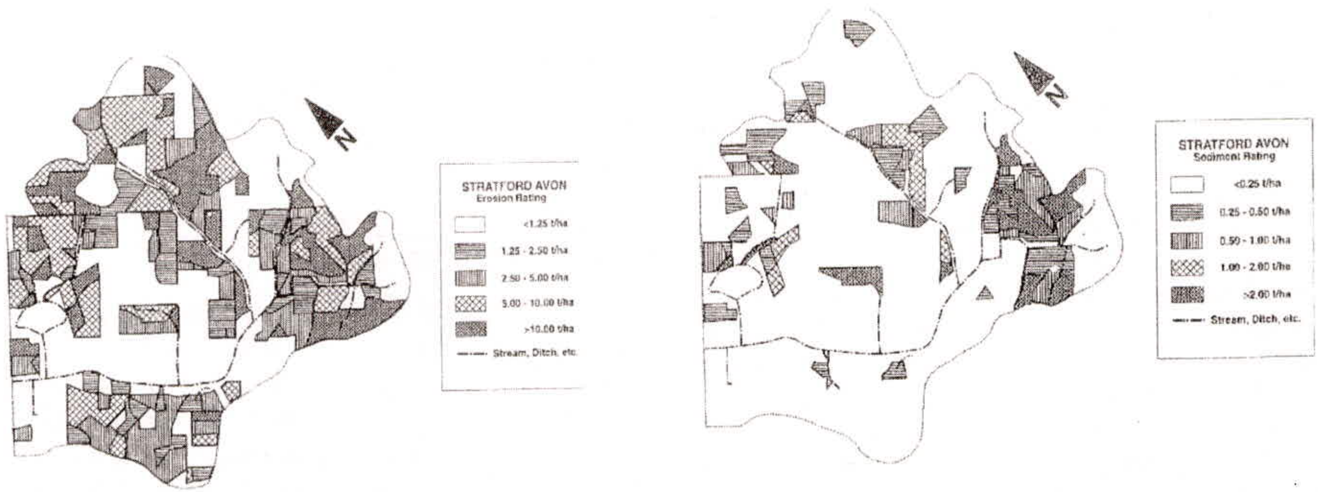
Spatial Distributions of Soil Loss and Sediment Yield

The spatial distribution sediment pollution (soil loss and sediment yield) form upland rolling watershed obtained by the application of GAMES for the spring period are presented in Figure 2 (Dickinson *et al.*, 1987; Rudra *et al.*, 2003). These data reveal that the spatial pattern of potential spring soil loss in the upland basin is highly variable (Figure 2(a)). The estimated long-term



(a) (b)

Fig. 1: Average annual distribution of stream flow (a) and sediment loads (b) in selected rivers in Southern Ontario

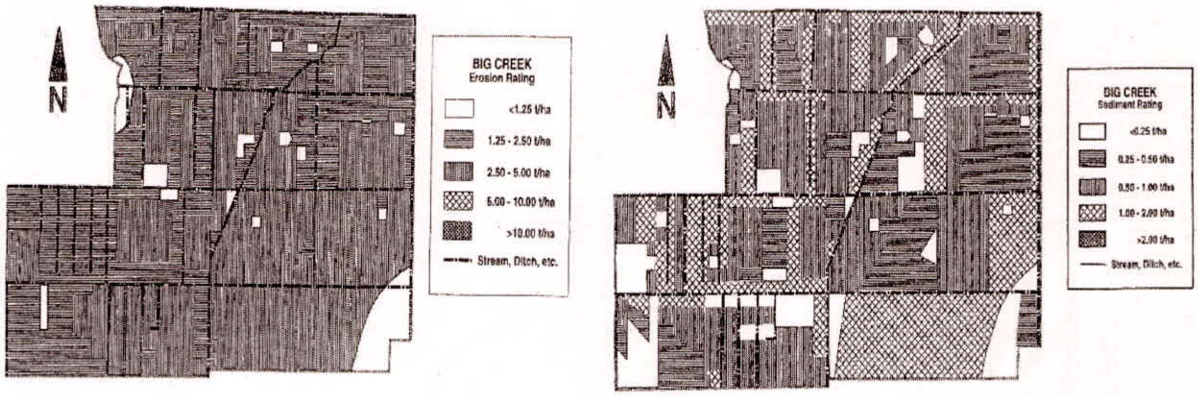


(a) (b)

Fig. 2: Spatial distribution of potential soil loss (a) and sediment yield (b) in an upland watershed

average spring gross erosion rate for this watershed is about 5 t/ha. This erosion rate is not very large; however, the individual field potential erosion rates are varying from 0 to 25 t/ha. These data also indicate that a major portion of the soil erosion is localized and originates from a very small portion of the watershed. About 45% of the watershed has an erosion rate more than 2.5 t/ha and this area has 95% contribution to the total watershed soil loss. Fifteen percent of the watershed has erosion rate greater than 10 t/ha, contributing 58% to the total watershed soil loss. Similar to the erosion the spatial sediment yield pattern is also highly variable (Figure 2(b)). The long-term spring sediment yield is 0.3 t/ha. A great majority of the sediment loads leaving the watershed emanate from a small percentage of the watershed area: Ninety five percent of the watershed has a sediment yield rate less than 2 t/ha and 73% less than 0.25 t/ha. Seventeen percent of the watershed area generates 79% of sediment loads and 11% generates 66% of the sediment loads.

Figure 3 presents the spatial pattern of potential soil loss and sediment yield from flat lowland watershed (Rudra *et al.*, 1993). The results are significantly different from those for the upland watershed. In this watershed the long-term average spring erosion rate is 2.5 t/ha. The erosion rate is much less spatially variable across the watershed (Figure 3(a)) with a range of 0 to 3.5 t/ha. The long-term spring sediment yield rate is 0.63 t/ha, and most sediment yields are in the range of 1.0 to 2.0 t/ha (Figure 3(b)). Only 3% of the watershed area has a sediment yield greater than 2 t/ha. The sediment generation across the watershed is uniform and sediment yield "hot spots" are not evident. Forty seven percent of the watershed contributes 81% of the sediment load with sediment yield rate greater than 0.5 t/ha. Thirty two percent of the watershed has



(a) (b)

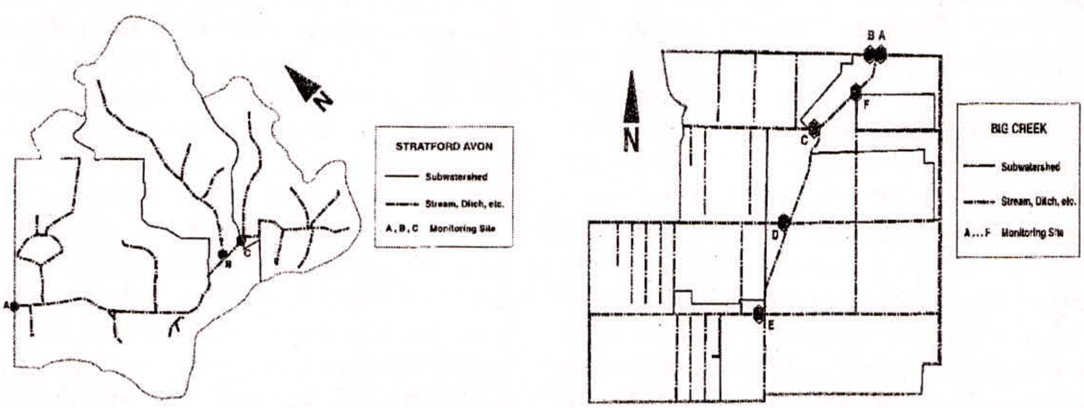
Fig. 3: Spatial distribution of potential soil loss (a) and sediment yield (b) in a lowland watershed

sediment yield less than 0.25 t/ha compared to 5% in the upland watershed.

These results clearly reveal the implication of spatial variability of soil loss and sediment yield (due to soil, land use, and topography) in the management of nonpoint source pollution. Upland watershed has erosion rate almost double than the lowland watershed while the sediment yield rate from the upland watershed is almost one-half that of lowland watershed. The upland watershed has low watershed deliver ratio (0.065) compared to lowland watershed (0.25). These variations are due to the spatial variability in soil and topography. In the upland watershed, soils are generally of medium texture, and rolling upland topography resulting in localized high soil loss. Rolling topography and the relatively high courser particles in the eroded soils create conditions favorable for deposition. However, in the localized area, generally close to the stream steep slope and highly erodible soils result high erosion rate, high sediment delivery ratio, and high sediment yield. In the lowland watershed fine textured soil and flat topography results in low soil loss. The eroded soil particles are fine; stay suspended for longer time and get more opportunity to reach the stream because flat topography and finer eroded soil particles do not create conditions favorable for deposition. Due to uniformity in soil and flat topography almost whole of the watershed area contributes to the sediment loads.

Implication of Spatial Variability in the Development of Monitoring Locations

Based on the spatial distribution of sediment yield areas given in Figures 2(b) and 3(b), in addition to the watershed outlets, hypothetical subwatershed monitoring sites were identified in both study watersheds (Rudra *et al.*, 2003). The identified monitoring sites are A, B and C in the upland watershed (Figure 4(a)) and sites A, B, C, D, E, and F in the lowland watershed (Figure 4b). The spring sediment loads estimated at these sites by application of GAMES model (calibrated for actual spring loads at the watershed outlet), are given in Table 1 and 2 for upland and lowland watersheds, respectively.



(a) (b)

Fig. 4: Map of upland watershed (a) and lowland watershed (b) including drainage pattern and the location of hypothetical monitoring locations

The estimated spring sediment loads from subwatersheds A, B, and C in the upland watershed are estimated to be 36, 25 and 39%, respectively of the total spring sediment load emanating from the entire watershed (Table 1). These three subwatersheds constitute 53, 28, and 19%, respectively, of the total watershed area. These data clearly show that subwatershed C is expected to contribute more sediment per unit area (0.63 t/ha) than subwatershed A (0.21) and B (0.27), and a monitoring station at the outlet of subwatershed C will be required to confirm that this subwatershed is a major contributor. This station will also be required to evaluate the impact of remedial strategies selected for reducing sediment load from this subwatershed. For the lowland watershed the soil loss range is relatively narrow and the sediment source areas are fairly uniformly spread across the watershed (Figure 3(b)). Subwatersheds B, C, and D contribute a greater percentage of the watershed spring sediment load with sediment yield rate of greater than 0.85 t/ha (Table 2). The subwatersheds B and C cover 33% of the watershed area and contribute 48% of the watershed spring sediment load. Subwatersheds B, C, and D, covering 11, 8, and 14% of the watershed area, contribute 16, 10, and 22%, respectively, to the watershed spring sediment loads. The sediment yield rates from subwatershed B, C, and D are almost double than the subwatershed F, and about 30 to 50% more than sunwateshed A. These data suggest that subwatershed B, C and D are the major contributors and the outlets of these subwatersheds require monitoring stations. However, the sediment yield rate from subwatesheds A and F are also more than 0.5 t/ha, a typical characteristic of lowland flat watersheds in southern Ontario, where few depositional areas exist and fine sediments remain in suspension all the way to the main drains. These subwatersheds are also significant contributors to the watershed spring sediment loads. In the lowland watershed it will be difficult to identify the sediment source areas and installation of monitoring station at the subwateshed outlet and will not be as beneficial as in the upland watershed.

Table 1: Spring Sediment Loads for the Selected Subwatersheds in the Upland Watershed

Upland Sub-watershed	*Area*		*Sediment Load*		
	ha	*%*	*t*	*%*	*t/ha*
A	287	53.4	59	36.2	0.206
B	150	28.0	41	25.1	0.273
C	100	18.6	63	38.6	0.63

Table 2: Spring Sediment Loads for the Selected Subwatersheds in the Lowland Watershed

	Area		*Sediment Load*		
	ha	*%*	*t*	*%*	*t/ha*
A	1175	35.6	583	27.6	0.67
B	370	11.2	330	15.6	0.91
C	252	7.6	219	10.4	0.87
D	475	14.4	468	22.1	0.99
E	405	12.3	266	12.6	0.51
F	623	18.9	247	11.7	0.40

Implication of Spatial Variability and Application of Remedial Strategies

The implication of spatial variability on the management of nonpoint source pollution has been examined by comparing the reduction in watershed spring sediment yield by application of remedial strategies (Table 3) (Dickinson *et al.*, 1990). Figure 5 presents the reduction in watershed spring sediment yield by application of remedial strategies given in Table 3 with moderate change in land management practice (30% reduction in the C factor of the USLE). The strategies B and C incorporate spatial variability of soil loss and sediment yield. Strategy A is based on random application and does not consider the impact of spatial variability. Strategy D considers the spatial variability of land slope and land use. The data clearly reveal the impact of strategies considering spatial variability of soil erosion and sediment yield. Targeting 10% of the upland watershed area (B-2) can result 30% reduction in watershed spring sediment where as 70% of the watershed area will need treatment to obtain 30 percent reduction in watershed spring sediment load by random application of remedial strategies (A). In the lowland watershed the application of targeted (based on spatial variability) is more effective than random remediation (Figure 5(b)) but not as efficient as upland watershed. Targeting 10% of the watershed area (B-2) can result 14% reduction in watershed spring sediment yield where as 100% of the watershed area will need treatment to obtain 30 percent reduction in watershed spring sediment yield by random application of remedial strategies (A). Application of strategy D [selection of fields based on land use (row crop) and slope greater than 5%] is only possible in upland watershed. In the lowland watershed the spatial variability in slope is so small that this strategy has no application. For the lowland watershed strategy C-1 and C-2 is expected to give similar results because most of the fields in the targeted area has sediment yield rate less than 1 t/ha and soil loss rate less than

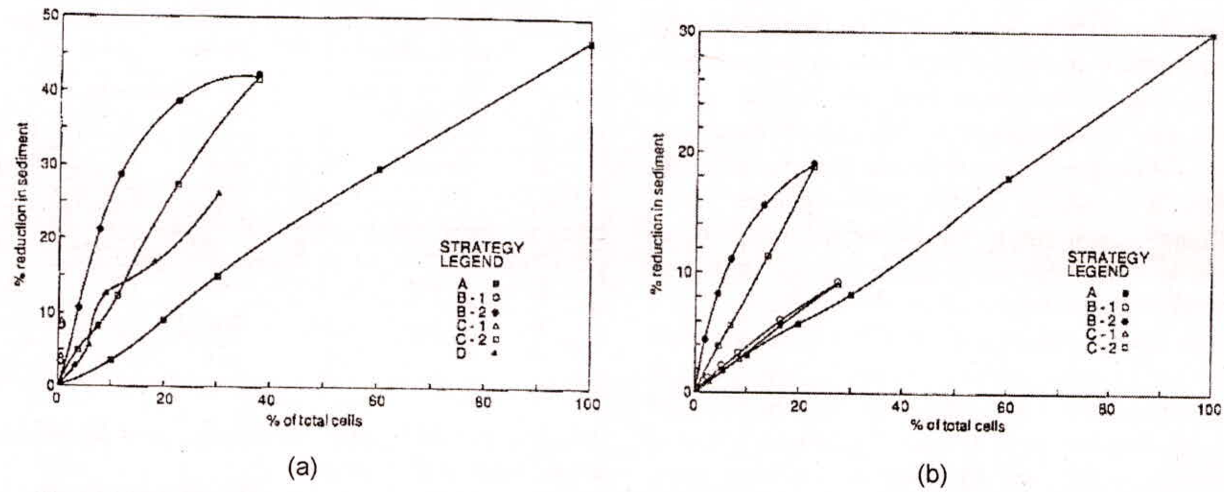


Fig. 5: Reduction in sediment yield from Upland watershed (a) and lowland watershed (b) as a results of application of management strategies involving changes in land use management

Table 3: Remedial Treatments for Watershed Management [a]

Strategy	*Description*	
A	Random selection of fields from the total area of the watershed in an increment of 10% of total number of fields in the watershed.	
B	Selection of fields from the targeted portion of the watershed in an increment of 10% of total number of fields in the targeted area	–1[b] Spring sediment yield before treatment of greater than one ton per hectare
		–2[c] Spring soil loss potential greater than three tons per hectare
C	Random selection of fields from the targeted areas in an increment of 10% of the total number of fields in the targeted area	–1[b] Spring sediment yield greater than one ton per hectare
		–2[c] Spring soil loss potential greater than three tons per hectare
D	Selection of fields based on land use (row crop) and topography (slope greater than 5%) in an increment of 10% of the total number of fields in the watershed	

[a] Adopted from Dickinson *et al.* (1990)

[b] Cells with the greatest sediment yield rate were treated first

[c] Cells with the greatest soil loss rate were treated first.

3 t/ha. To further illustrate the implication of spatial variability in the management of nonpoint source pollution let us consider that the objective has been to reduce the watershed spring sediment yield by 10 and 30%. The percentage of the watershed area needed to achieve these targets under various remedial strategies and moderate change in land use management practices is given in Table 4. These data show that due to more spatial variability soil loss and sediment sources associated with spatial variability of soil, land use, topography the upland watershed requires less area than the lowland watershed to achieve set targeted reduction in watershed spring sediment yield. Due to spatial uniformity of soil and topography in the lowland watershed, the spatial variability in the magnitude and rate of soil loss, sediment yield, and the location of soil loss and sediment source sources is also small which results non applicability of remedial D for 10% reduction in watershed spring sediment loads and strategies B-2, C-2 and D for 30% reduction in watershed spring sediment loads.

Table 4: Percentage of the Watershed Area Needed to Achieve 10 and 30% Reduction in Watershed Spring Sediment Yield with Various Remedial Strategies with Moderate Change in Land Use Management

Watershed		*Remedial Strategy*			
	Sediment Load Reduction (%)	*A*	*B-2*	*C-2*	*D*
		Watershed Area (%)			
Upland	10	22	3	8	7
	30	62	12	25	NA
Lowland	10	36	2	6	NA
	30	100	NA	NA	NA

CONCLUDING REMARKS

The examples presented in this paper have clearly demonstrated the implication of seasonality variant spatial variability in the modeling, monitoring, and management of nonpoint source pollution. The knowledge of seasonal variant and spatial variability of pollution source is essential for the development of economically feasible, environmentally sustainable, and socially acceptable management practices and remedial strategies. Consideration of seasonal variant spatial variability is also essential for the planning and development of monitoring program to assess the sources and magnitude of pollution in a watershed, and to evaluate the performance of best management practices. The knowledge of spatial variability of pollution sources, watershed on the landscape and areas in a watershed, are so important for development of nutrient trading scenarios.

REFERENCES

Clark, D.J. (1981). "An expression for determining sediment delivery radio." M.Sc. Thesis, University of Guelph, Guelph, Ontario.

Dickinson, W.T., Rudra, R.P. and Clark, D.J. (1986a). "A delivery ratio approach for seasonal transport of sediment." *Drainage Basin Sediment Delivery: IAHS Pub. No. 159* 237–251.

Dickinson, W.T., Rudra, R.P. and Wall, G.J. (1986b). "Discrimination of soil erosion and fluvial sediment areas." *Can. Jour. Earth Sci.*, 22, 1112–1117.

Dickinson, W.T., Rudra, R.P. and Wall, G.J. (1987). "Identification of soil erosion and fluvial sedimentation problems." *Hydrologic Processes*. 1, 111–124

Dickinson, W.T. and Green, D.R. (1988). "Characterization of sediment loads in Ontario streams." *Can. J. Civil. Eng.*, 15, 1067–1079.

Dickinson, W.T., Rudra, R.P. and Wall, G.J. (1990). "Targetting remedial measures to control non-point-source pollution." *Water Resour. Bull.*, 26(3), 499–507.

Ontario Ministry of Agriculture and Food (OMAF). (1975). "Ontario soils—Physical, chemical and biological properties and soil management practices", *Publication 492, Agdex 500, Ontario Ministry of Agriculture and Food,* Toronto, Ontario.

Rousseau, A., Dickinson, W.T. and Rudra, R.P. (1987a). "Computational methods to conduct nonpoint source pollution studies." *App. Eng. in Agri.*, 3(2), 252–257.

Rousseau, A., Dickinson, W.T. and Rudra, R.P. (1987b). "Evaluation of best management practices of phosphorus nonpoint source pollution." *Can. Agri. Eng.*, 29(2), 163–168.

Rousseau, A., Dickinson, W.T., Rudra, R.P. and Wall, G.J. (1988). "A phosphorus transport model for small agricultural watersheds. " *Can. Agri. Eng.*, 30(2), 213–220.

Rudra, R.P., Dickinson, W.T., Clark, D.J. and Wall, G.J. (1986). GAMES—"A screening model of soil erosion and fluvial sedimentation in agricultural watersheds", *Canadian Water Resources Journal*, 11(4), 58–71.

Rudra, R.P., Dickinson, W.T., Sharma, D.N. and Singh, S.P. (1994). "Employing a watershed model as a Basis for planning a sediment monitoring program." *Can. Water Resour. J.*, 19(4), 289–303.

Wall, G.J., van Vliet, L.P.J. and Dickinson, W.T. (1978). "Contribution of sediments to the Great Lakes from agricultural activities in Ontario", *IJC Technical Report re: PLUARG, International Joint Commission*, Windsor, Ontario.

Wall, G.J., Dickinson, W.T. and van Vliet, L.P.J. (1979). "Agricultural sources of fluvial suspended sediments", *Progress in Water Technology*, 11(6), 481–499.

Water Quantity Resources of Ontario (WQRO) (1984). *G. Lyon's Litho Limited, Fort Erie*, ON, Canada.

Wischmeier, W.H. and Smith, D.D. (1978). "Predicting rainfall erosion losses—A guide to conservation planning", *Agricultural Handbook No. 537, United States Department of Agriculture*, Washington, D.C.