A Delivery Ratio Approach for Seasonal Transport of Sediment

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ABSTRACT An expression for determining spatially distributed sediment delivery ratios has been developed. This expression is spatially and temporally compatible with existing methodologies for determining potential in-situ gross erosion. The expression makes use of easily quantifiable physical and hydrological characteristics of the watershed and can be applied at a watershed discretization level of field size or smaller. The expression has been calibrated on the Canagagigue West Watershed in Ontario. Sensitivity analyses of related parametric values to a characteristic range of variable values have been carried out together with the sensitivity of actual delivery ratios to changes in related variable values. The expression is practical for application in watershed studies, can be used to delineate critical sediment source areas within a watershed, and has the potential to predict the effect of proposed remedial measure strategies on delivery ratios.

INTRODUCTION

During the past decade, the pollution of surface waters by sediment and associated chemicals originating from non-point sources has become acknowledged as a widespread and serious problem (Novotny and Chesters, 1981). An example of this problem has been revealed in the Great Lakes Basin of North America, where about 60 million tonnes of sediment flow annually into the Great Lakes, and about 3000 tonnes of phosphorus are transported annually into Lake Erie alone from agricultural lands in Ontario (International Reference Group on Great Lakes Pollution from Land Use Activities, 1978). Studies in the Great Lakes area have clarified not only the nature and extent of non-point source pollution problems, but also the need for methods to ascertain key source areas of the pollutant materials. Determination of such source areas would allow the more effective and economical implementation of site-specific remedial measures.

The location of sediment source areas, and sources of sediment-associated pollutants (e.g. phosphorus, heavy metals, pesticides), has often been based on indicators of soil erosion such as land use and land slope. Such an approach assumes that both the sediment yield and the spatial distribution of sources of stream sediments are determined by source erosion processes and not altered significantly by variations in sediment transport mechanisms. However, it has been noted (Wall et al., 1978; Dickinson and Pall, 1982) that sediment source areas do not necessarily coincide with major soil erosion areas, due to variations in the capacity of different parts of a watershed to transport particulate materials. Therefore, methods for the delineation of sediment source areas, and for the locating of cost-effective sediment control measures, must take into account factors associated with sediment delivery opportunities as well as soil detachment processes and rates.

The objectives of the research reported in this paper have included the development of a sediment micro-delivery expression for the estimation of the spatially and seasonally variable proportion of sediment transported from field to field and from field to stream in small agricultural watersheds. The expression was to be used in conjunction with a silo erosion model in which estimates of soil loss were to be made for field-size areas on a seasonal basis (Cook et al., 1985).

LITERATURE REGARDING WATERSHED SEDIMENT DELIVERY

The transport of sediment through rural basins has been dealt with by implicit and explicit means in the literature. The implicit approaches have predicted watershed sediment yield directly from drainage basin variables and parameters, without explicitly evaluating sediment delivery. For example, the deterministic models of Jansen and Painter (1974) and McPherson (1975) related average annual watershed sediment yield to climatic and topographic variables such as mean annual temperature, drainage area, mean land slope, and basin elevation. Williams and Berndt (1976) and Beasley et al. (1981) developed discrete event deterministic sediment yield models in terms of the Universal Soil Loss Equation (U.S.L.E.) and a runoff factor involving the volume of storm runoff and the peak flow rate. Stochastic methods have also been used for the direct estimation of watershed sediment yield. Bobrovitskaya et al. (1977) incorporated a stochastic component in the energy term of their storm event and seasonal sediment yield model. Sharma and Dickinson (1979) predicted daily and monthly sediment yields from runoff and sediment yield time series.

The explicit approaches have dealt more directly with sediment delivery, and watershed sediment yield has been determined from a combination of gross erosion and sediment transport components. Lumped methods were developed initially to provide a linkage between on-site erosion estimates and downstream sediment measurements. That is, given an approach such as the U.S.L.E. for estimating gross erosion, a sediment delivery component was required for the prediction of sediment yield. The sediment delivery ratio, defined as the ratio of sediment delivered at the basin outlet to the gross erosion estimated to occur in the basin, has been related to such watershed parameters as drainage area, relief ratio, and U.S. Soil Conservation Service curve numbers (Renfro, 1975; Williams, 1977; U.S. Army Corps of Engineers, 1979). Such lumped delivery ratio expressions have afforded a means of predicting broad order-of-magnitude estimates of sediment yield, but have not allowed for the taking into account of variations in delivery opportunities in time and space (Walling, 1983).

To overcome shortcomings of the lumped approach noted above, other explicit but distributed methods have dealt with sediment delivery on a field scale. Transport factors, or micro-delivery ratios, expressing the ratio of sediment delivered at a field or small land cell outlet to the gross erosion estimated for the small area, have been evaluated in terms of relative field slopes and flow rates (Kling and Olson, 1974). Other field scale models have explored sediment delivery in terms of interrill and rill micro-delivery ratios (Foster et al., 1977), or by evaluating the transport capacities of forms of overland flow (Onstad and Foster, 1975; Tollner et al., 1976; Alonso et al., 1981). This exploration of sediment delivery in small units of time and space has been extremely informative, but the delivery ratio components of watershed sediment yield models which have been developed from such considerations have been either too simplistic to yield a realistic picture or too complex for practical application. There is still a need, therefore, for an approach to describing sediment delivery throughout a watershed which embodies generally accepted physical principles pertaining to sediment transport while maintaining a level of practicality that will allow the method to be used in conjunction with gross erosion estimates for the estimation of watershed sediment yield and the delineation of critical source areas within a watershed.

DEVELOPMENT OF A DELIVERY EXPRESSION

Physical principles significant to the development of a watershed sediment delivery expression have become evident in the literature regarding sediment transport in stream channels and the design of sediment settling basins. Studies regarding the horizontal movement of sediment in channels by convective transport (Vanoni, 1946; Einstein and Chien, 1954; Bagnold, 1957; Vanoni and Brooks, 1957; and Yalin, 1977), the role of turbulence in sediment suspension (Vanoni, 1963; Willis and Coleman, 1969; Johnson and Moldenhauer, 1970), and the nature of shallow overland flow (Woolhiser et al., 1971) have revealed that the efficiency of sediment transport in a channel varies directly with the average flow velocity in the channel and inversely with the fall velocity of the entrained sediment (Graf, 1971). And recent findings of Haan and Barfield (1978) have confirmed earlier observations of Camp (1943) and Rouse (1950) that the efficiency of sediment removal in settling basins is directly related to the length of the basin and the fall velocity of the entrained sediment, and inversely related to the average flow velocity through the basin. It is clear, therefore, that the velocity of the transporting fluid, the length of the flow path, and physical characteristics of the entrained sediment are prime factors to be considered for a sediment delivery expression.

With the assumption that physical characteristics of entrained sediment are not likely to vary spatially across small agricultural watersheds, the length of the overland flow path and the velocity of overland flow have been selected for the development of the following expression for micro-delivery ratio. Further, possible hydraulic effects of runoff entering a field-size area from upslope areas have been assumed to be negligible. Then,

$$DR = f(V/L) \tag{1}$$

where DR = the micro-delivery ratio from one location to another in a watershed (i.e. from field to field or from field to stream),

V = the average velocity of overland flow between locations, and

L = the length of the surface drainage flow path between locations.

Dimensional analysis of equation (1) indicates that the micro-delivery ratio varies inversely with the travel time of overland flow.

Overland flow studies based on kinematic wave theory (Woolhiser et al., 1971; Davis et al., 1978), and an adaptation of Manning's equation for overland flow (Ree et al., 1977), reveal that the average overland flow velocity is a function of surface roughness, surface gradient, and depth of flow. Selecting Ree's equation,

$$V = \frac{1}{n} S^{0.5} D^{0.67} \tag{2}$$

where n = Manning's surface roughness coefficient,

S = the slope gradient of the soil surface, and

D = the depth of overland flow.

In order to use equation (2) in a seasonal or annual rather than a storm event time frame, it is necessary to replace the absolute depth of flow term with a relative term which reflects the ability of a designated small area to generate surface runoff during characteristic events within the time frame being considered. This term must also reflect spatial variations in the generation of surface runoff, in accord with the dynamic contributing area concepts of hydrologic response (Betson, 1964; Hewlett and Hibbert, 1965; Dickinson and Whiteley, 1970). Introducing the hydrologic coefficient, Hc, to represent a location's capability to generate surface runoff in a selected season.

$$V = \frac{1}{n} S^{0.5} Hc \tag{3}$$

Further, $DR = f\left(\frac{1}{n} S^{0.5} \frac{Hc}{L}\right)$ (4)

Equation (4) can be written as a simple equality,

$$DR = \alpha \left[\frac{1}{n} S^{0.5} \frac{Hc}{L}\right]^{\beta} \tag{5}$$

where α, β = constants;

or $DR = \alpha\, (t^{1})^{\beta}$ (6)

where $t^{1} = \frac{1}{n} S^{0.5} \frac{Hc}{L}$

Equations (5) and (6) apply to delivery from one location to an adjacent location. To determine the delivery from one location to a more distant location (e.g. from a field, across several other fields, to a stream),

$$DR = \alpha \left[1 \Big/ \sum_{j=1}^{m} n_j \frac{1}{S_j^{0.5}} \frac{L_j}{Hc_j}\right]^{\beta} \tag{7}$$

where DR = the micro-delivery ratio from a field location to the stream,

m = number of downslope fields, and

j = jth field along the flow path.

In situations where the main stream system can be assumed to deliver 100 percent of the sediment transported to it, equation (7) represents the micro-delivery ratio from each field location to the watershed outlet.

Application of equations (5) and (7) requires that the constants α and β be determined from calibration on a watershed on the basis of gross erosion estimates for the fields or land cells and time frame selected, and the associated watershed sediment load measured at the outlet.

STUDY AREA AND DATA BASE

The Canagagigue West Watershed was selected as a study site for calibration of the micro-delivery ratio expression. This watershed, studied extensively during the PLUARG program, consists of 1860 ha in Wellington County in Southern Ontario. Local topography is flat to gently undulating; and the main surficial soil texture is loam, with small areas of organic soil and alluvial sediments. The drainage density, based on major spring drainage channel delineation, is about 1100 m/km.

Agricultural activities in the area are predominantly mixed farming, including dairy, beef, and swine operations. Silage corn, small grains, and hay are the main crops; and less than ten percent of the area remains as woodlots. Frank and Ripley (1977) have reported that crop residues are generally removed from the fields for farm use as livestock feed and litter; and cropland is ploughed in October, followed by secondary tillage in May.

Separate maps of land use, soil type, and land slope class were prepared for the watershed at a base scale of 1:5000. The maps were prepared from data obtained from aerial photographs, topographic maps, and land use, soils and cropping surveys. A composite overlay of the three maps was developed and the watershed was subdivided into irregularly shaped land cells, each of which was characterized by a single land use, a single soil type, and a single slope class (Figure 1 reveals the relative size and shape of the land cells). Representative values of the parameters required for calculation of gross erosion by means of the U.S.L.E. were estimated for each land cell for each of three seasons in the year: spring (February through May), summer (June through September), and winter (October through January). The seasonal application of the U.S.L.E. has been described by Cook et al. (1985). Figure 1 reveals the shape and size of the land cells in the watershed, and the associated gross erosion estimates.

For each land cell, it was also necessary to determine n and Hc values for the micro-delivery ratio expression. Length and slope of flow path were already available from the erosion calculations. Estimates of Manning's n for overland flow over various soil covers were made on the basis of guidelines presented by Foster et al. (1980); and a procedure was developed for the calculation of seasonal n values, taking into account the soil and crop management stages (Cook et al., 1985).

Hydrologic coefficient values were determined for each land cell for each season on the basis of three classes of hydrologic contributing areas. A cell was classed as a primary contributing area in a given season if it was near a stream, was imperfectly or more poorly drained,

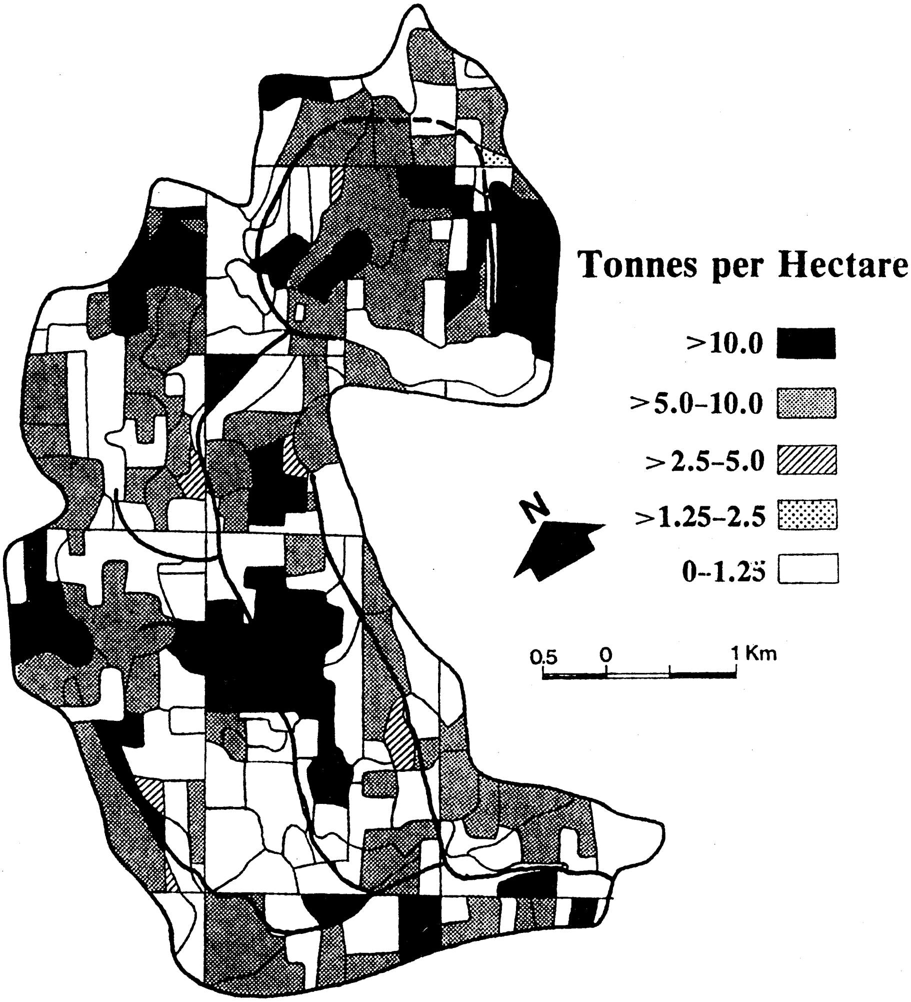

Figure 1 - Map of Canagagigue West Watershed, revealing shape and size of land cells and associated gross erosion estimates in tonnes per hectare.

or exhibited bare soil. A cell was classed as a tertiary contributing area if it was in a well-drained upland location, was distant from a stream, or involved a land depression. Cells not falling into either of the above categories were classified as secondary contributing areas. Further, considering land use, if the land cell was not primary and was cropped in hay or pasture, it was classed tertiary; if the cell was cropped in corn or beans, it was classed secondary. The Hc value assigned to each cell was established relative to a primary contributing area value of 1.0. For spring conditions, primary and secondary and often tertiary areas were assigned Hc values of 1.0; for summer conditions, the areas were assigned values of 1.0, 0.10, and 0.05 respectively.

The surface drainage system was mapped for the basin, and the lengths of overland and stream flow associated with each land cell were determined. The stream channels were observed to be neither aggrading or degrading actively, and all sediment reaching the main streams was assumed to be deliverd to the watershed outlet.

Sediment yield values were determined on the basis of suspended sediment measurements taken over several years by Environment Canada at their Station 02GA036 near Floradale at the watershed outlet. A representative spring sediment load of 2365 tonnes, amounting to about 80 to 85 percent of the annual load, was selected as a basis for spring calibration of the model. Knap (1978) estimated that 30 percent of the load arose from streambank erosion, leaving 1655 tonnes of sediment attributable to delivery from field erosion in the watershed.

MODEL CALIBRATION AND PARAMETER SENSITIVITY

Optimum values of α and β were determined using the optimization function,

$$E = Sf - \sum_{j=1}^{N} g(j) - dr(j) \tag{8}$$

where E = the error difference between observed and predicted downstream sediment loads for an assumed set of α and β values,

Sf = the portion of the sediment load observed at the water outlet attributed to field erosion sources,

g(j) = the gross erosion predicted for the jth land cell,

dr(j) = the micro-delivery ratio predicted from the jth land cell to the stream, and

N = the number of land cells in the watershed.

An automatic optimization algorithm presented by Rosenbrock and Storey (1966) was used to sequentially vary values of α and β until the optimization function was minimized. In the event that the micro-delivery ratio associated with a cell was calculated to be greater than 1.0, the ratio was set equal to 1.0.

The calibrated expression for micro-delivery of sediment from any land cell to the stream under spring conditions on the Canagagigue West Watershed was determined to be,

$$DR = \text{minimum of } 9.53(t^{1})^{0.79} \text{ and } 1.0 \tag{9}$$

Figure 2 reveals the range and spatial distribution of the micro-delivery ratio values; and Figure 3 reveals the land cell sediment yields obtained from the product of the delivery ratio and gross erosion values.

Sensitivity analyses were conducted to explore the possible variability of and with changes in values assigned to the hydrologic coefficient and surface roughness parameters. The Hc value for primary contributing areas was varied from 0.6 to 1.0, for secondary areas from 0.10 to 0.60, and for tertiary areas from 0.001 to 0.10. The various combinations of these values that were examined are shown in Table 1, along with the resulting optimum values of α and β. It is quite clear

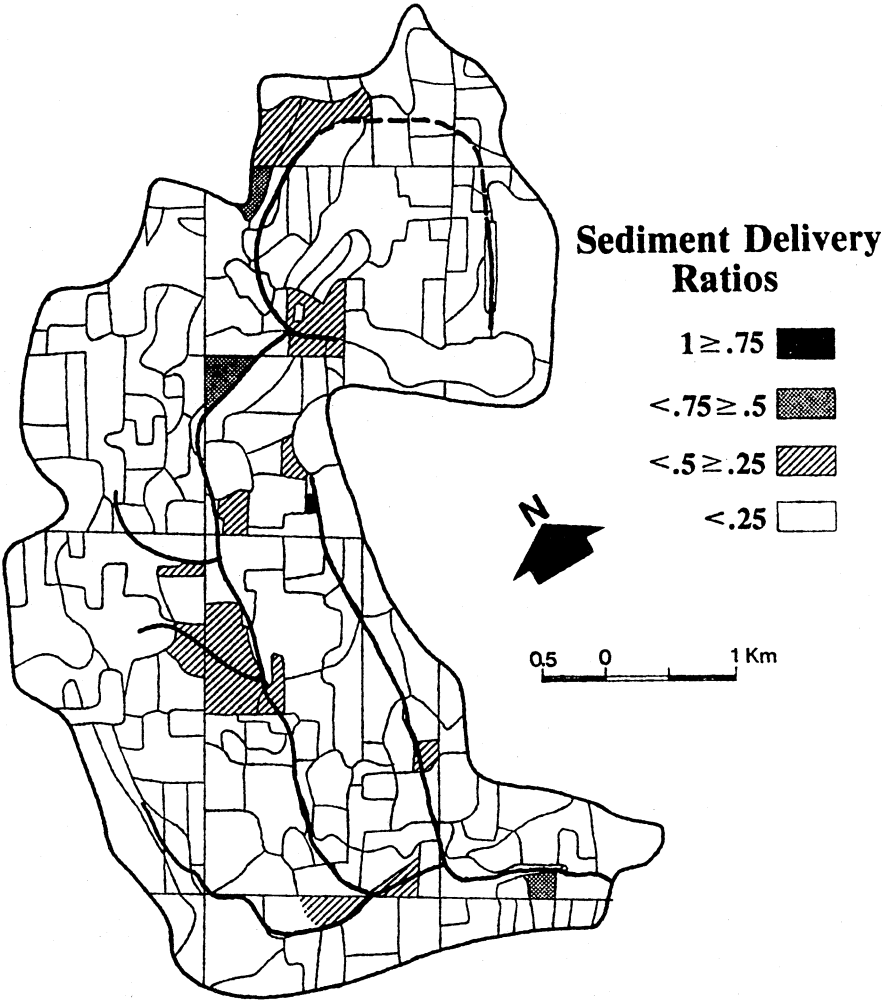

Figure 2 - Calibrated sediment delivery ratios for spring season.

from there results that the calibrated values of α and β were not sensitive to the specific values of Hc selected for the three classes of contributing areas.

Regarding the sensitivity of α and β to perturbations in surface roughness estimates, various combinations of n values assigned to conditions of surface roughness associated with converging flow and diverging flow in grass, and with flow through wooded areas, are shown in Table 2 along with the resulting α and β values. Again, it is apparent that the calibrated values of α and β were not sensitive to the values of n selected for various types of ground cover.

EFFECTS OF LAND SLOPE, FLOW LENGTH, SURFACE ROUGHNESS, AND HYDROLOGIC CONDITIONS ON SEDIMENT DELIVERY

The calibrated expression for micro-delivery ratio, equation (9), was used to study the sensitivity of delivery to changes in land slope, flow length, surface roughness, and hydrologic coefficient. The range of

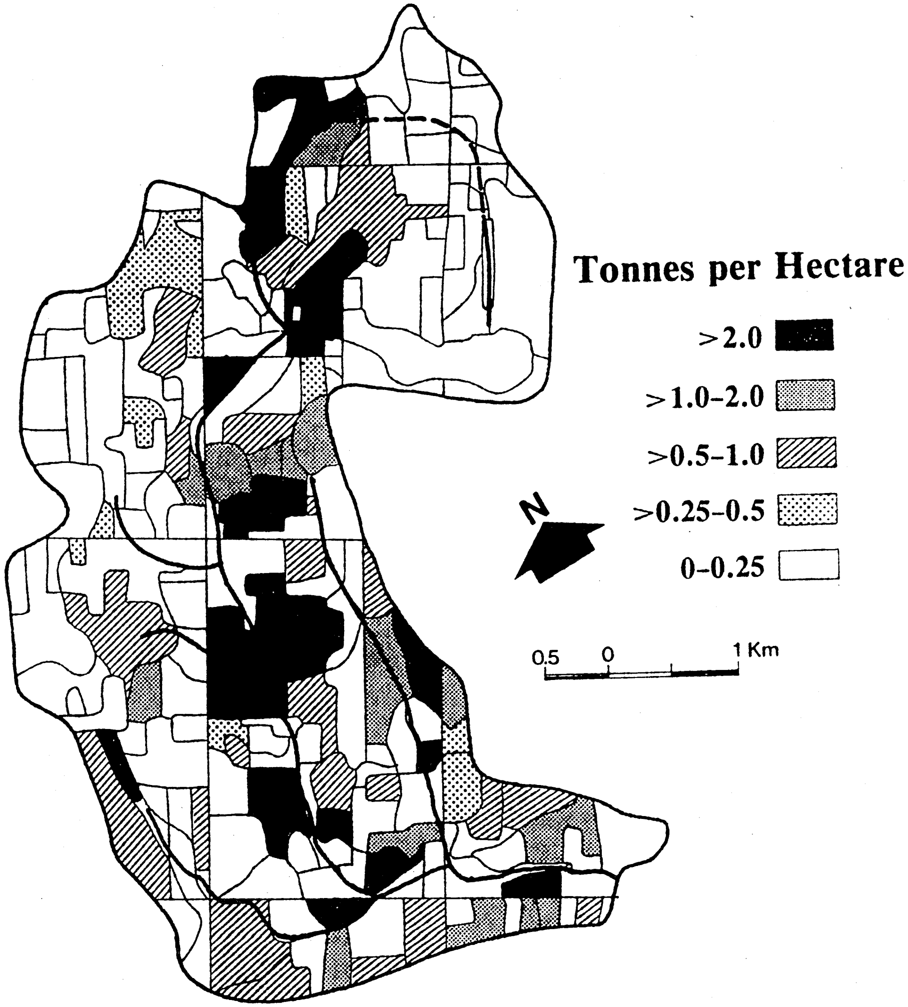

Figure 3 - Estimated land cell sediment yields in tonnes per hectare.

values considered was similar to that used for the calibration. Delivery ratio response surfaces were generated for the three categories of hydrologic coefficient, three flow lengths (10, 33, and 100 m), a range of surface roughness values between 0.08 and 0.80, and a range of surface slopes between 1 and 10 percent. Sample response surfaces are shown in **Figures** 4, 5 **and** 6.

The results suggest that the micro-delivery ratios across a watershed can vary significantly as a result of variations in the variables. Minor slope changes in areas with slopes less than five percent result in slight changes in the delivery ratio. Increases in flow length in areas with slopes less than five percent result in pronounced decreases in delivery ratio. Delivery ratios also decrease rapidly with increases in surface roughness values within the range of 0.08 to 0.24. With respect to the hydrologic classifications, the delivery ratios are noticeably

Table 1: Optimum values of α and β, calibrated for various sets of values assigned to the hydrologic coefficient categories.

HYDROLOGIC COEFFICIENT VALUES			CALIBRATED PARAMETER VALUES	
PRIMARY CATEGORY	SECONDARY CATEGORY	TERTIARY CATEGORY	A	B
1.0	0.50	0.08	10.26	0.74
		0.06	10.11	0.73
		0.04	10.21	0.73
		0.02	10.24	0.73
		0.001	10.26	0.72
1.0	0.50	0.08	10.26	0.74
	0.40		10.33	0.74
	0.30		10.22	0.73
	0.20		10.22	0.72
	0.10		10.06	0.71
	0.60		11.24	0.77
1.0	0.50	0.80	10.26	0.74
0.95			10.33	0.74
0.90			10	
0.85			10.24	0.72
0.80			10.40	0.72
0.75			10.06	0.71
0.70			10.00	0.70
0.65			9.77	0.69
0.60			9.87	0.68
0.55			9.87	0.68
0.80	0.50	0.04	10.06	0.71
0.80	0.30	0.40	9.90	0.69
1.00	0.30	0.04	10.24	0.72
0.80	0.50	0.08	10.00	0.70
0.80	0.30	0.01	9.53	0.67
1.00	0.12	0.05	10.02	0.70
1.00	0.10	0.01	9.88	0.69

greatest in the primary contributing areas and least in the tertiary areas.

Several observations can also be made with respect to the effect of simultaneous changes in two or more of the variables. Increasing roughness and decreasing slope result in a noticeable decrease in delivery ratio. This effect is most evident over short travel lengths. As the travel length increases, the resultant effect of slope and roughness changes is decreased. For a given length and hydrologic category, the delivery ratio is more sensitive to changes in roughness than changes in slope. This effect is most apparent in areas with slopes greater than five percent. With the exception of short flow length situations in primary contributing areas, the variability of the delivery ratio is most pronounced in steep slope/low roughness zones (i.e. slopes 5 percent, roughness 0.24). The delivery ratio response surface for short flow lengths in primary contributing areas shows a reverse trend. Devliery ratios equal the maximum value of 1.0 in the steep slope/low

Table 2: Optimum values of α and β, calibrated from various sets of values assigned to surface roughness conditions.

ROUGHNESS			CALIBRATED PARAMETERS	
GRASS CONVERGED FLOW	GRASS DIVERGED FLOW	WOODS	A	B
	0.09		9.54	0.81
0.07	0.20	0.65	9.53	0.79
	0.14		9.54	0.80
	0.16		9.54	0.79
	0.18		9.53	0.79
	0.22		9.49	0.79
	0.24		10.86	0.81
	0.12		9.54	0.80
0.01	0.20	0.65	7.98	1.25
0.03			10.03	0.96
0.04			8.98	0.87
0.05			9.51	0.84
0.06			9.54	0.81
0.07			9.53	0.79
0.09			10.97	0.78
0.07	0.20	0.65	9.53	0.79
		0.30	9.53	0.79
		0.40	9.53	0.79
		0.25	9.53	0.79
		0.60	9.53	0.79
		0.70	9.53	0.79
		0.80	9.53	0.79
		0.90	9.58	0.79
		0.50	9.53	0.79

roughness zone, while there is moderate variability in the shallow slope/high roughness zone.

It is interesting to note the possible implications of the above effects for sediment control remedial strategies. In areas with slopes greater than five percent and close to a water course, land use should be restricted to pasture, forage, or woodlot in order to maintain relatively low delivery ratios. When such areas are primary contributing areas, land use must be woodlot in order to significantly reduce the delivery ratio below 1.0. With the exception of primary contributing areas, the most significant reduction in delivery ratio results from land use changes from fall ploughed to grass cover. The average reduction in delivery ratio as a result of this land use change is in the order of 40 percent.

CONCLUSIONS

It has been possible to develop and calibrate a micro-delivery ratio expression to estimate the proportion of sediment transported from field-sized areas to adjacent areas and to the stream and outlet of a small agricultural watershed for a seasonal time frame. The optimized parameters of the expression are very stable, and the values of delivery ratio predicted to occur in the watershed vary over a wide range,

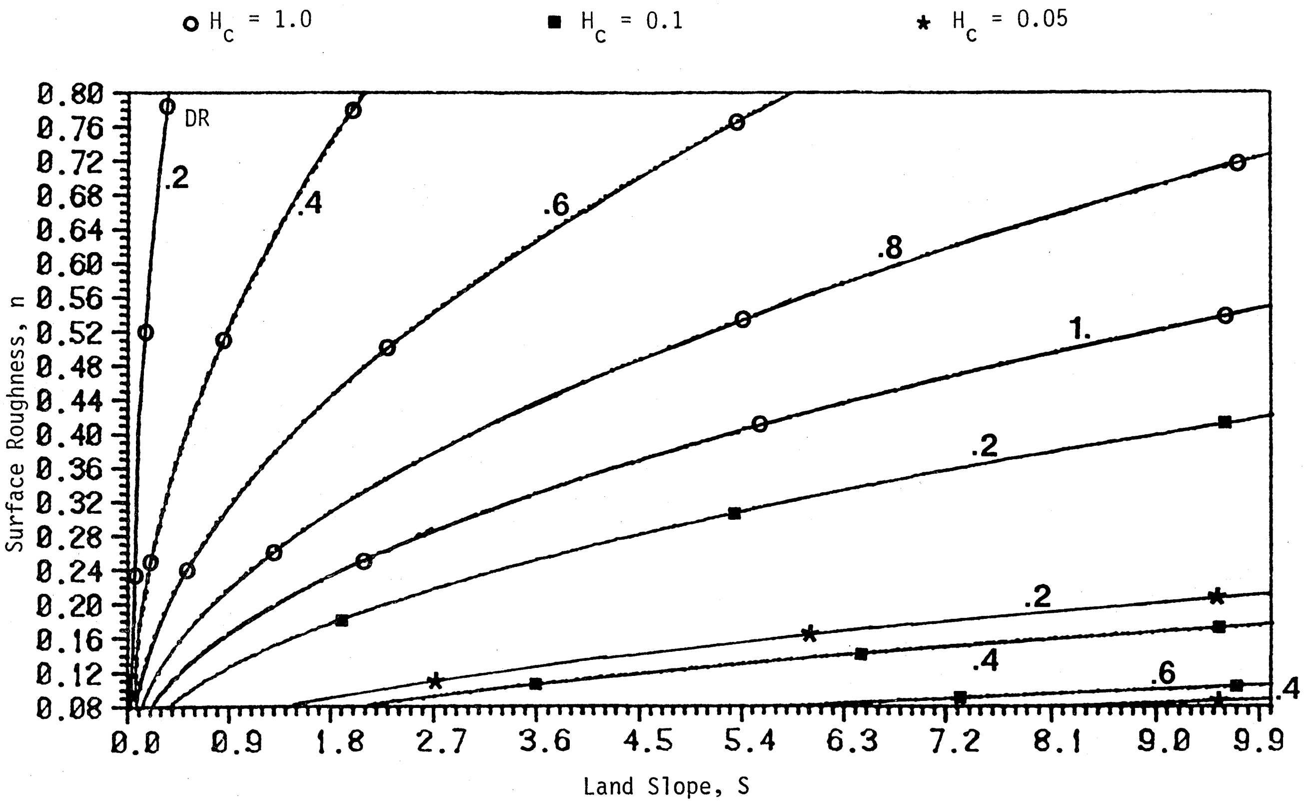

Figure 4 - Delivery ratio response surface for overland flow length of 10 metres.

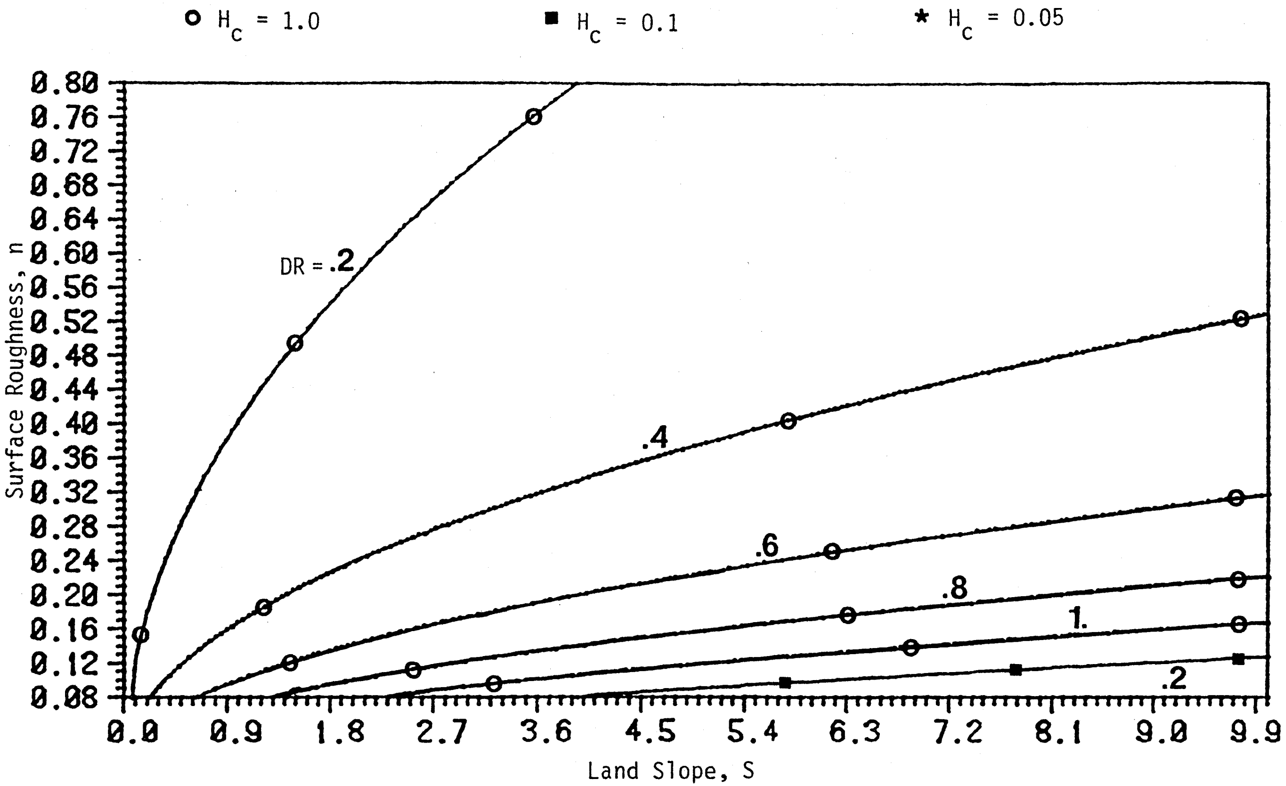

Figure 5 - Delivery ratio response surface for overland flow length of 33 metres.

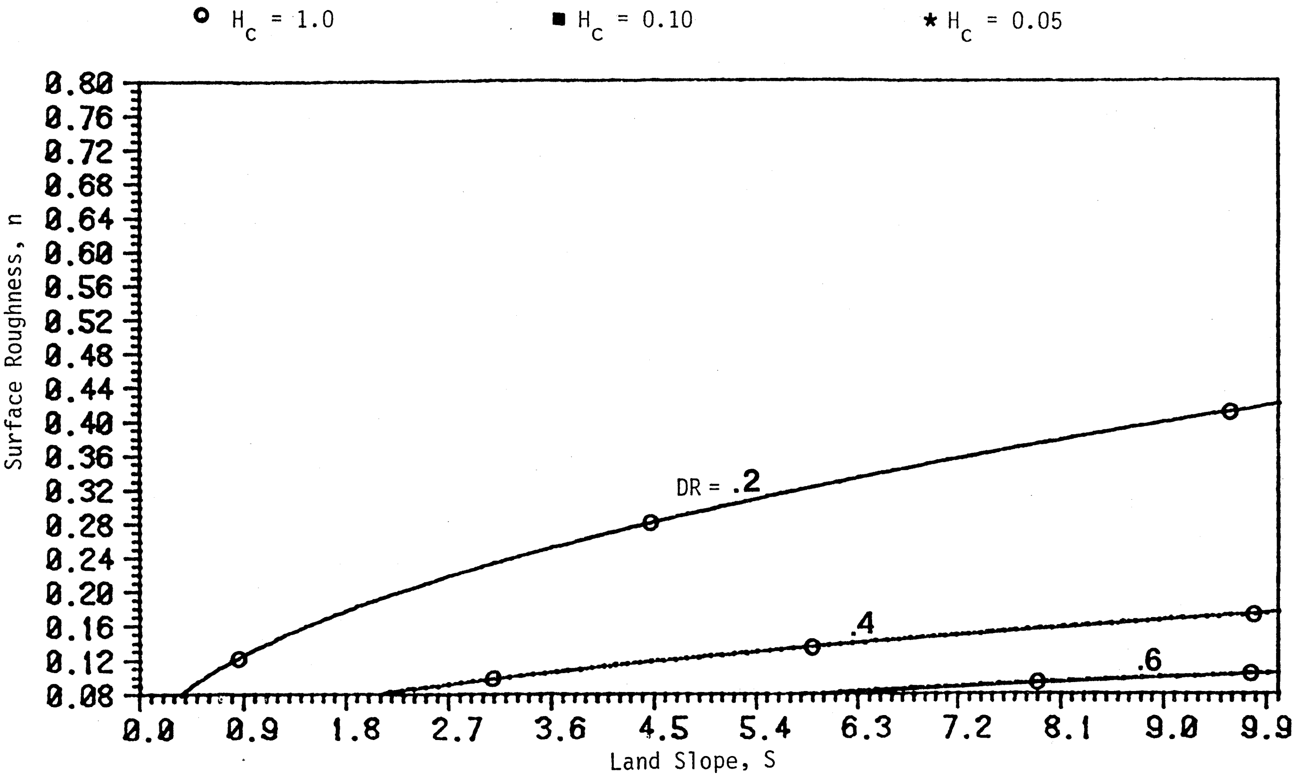

Figure 6 - Delivery ratio response surface for overland flow length of 100 metres.

revealing effects of land slope, flow length, surface roughness, and hydrologic conditions. The range and spatial distribution of the delivery ratio values are consistent with expectations based on the literature and qualitative field observations, but require quantitative field validation prior to wider application.

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