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Impacts of soil characteristics on soil erodibility

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ABSTRACT Field observations from two small drainage basins in the temperate climate of Southern Ontario, Canada, have been explored in the light of laboratory experiments for the purpose of identifying key soil characteristics affecting soil erodibility. High soil erosion and transport rates during and immediately following spring thaw temperature and soil water conditions appeared to be linked to the presence of low soil density, high soil water content and resulting low shear strength values in the surface soils. Laboratory tests on agricultural soil samples from the area verified the vulnerability of the soils to such density and water content conditions. Although the existing data base is acknowledged to be sparse, it is hypothesized that further examination of surface soil shear characteristics may be extremely fruitful in clarifying erosion processes in not only spring thaw but also arid soil/water environments.

INTRODUCTION

The accelerated loss of productive soil due to erosion and the subsequent deposition of transported material in downstream river and lake systems have become acknowledged as a serious problem in many regions of the world, including the lands adjacent to the Great Lakes of North America (International Joint Commission, 1978). The severity of this problem has focussed attention on the need to more adequately characterize soil losses - quantitatively, in areal extent, and in temporal distribution. Although much has been accomplished in this respect in recent years, soil erosion remains a complex phenomenon which is not yet sufficiently well understood to allow precise prediction.

Research has identified a number of factors which explain much of the spatial variation in annual soil loss (e.g. Olson & Wischmeier, 1963; Olson *et al.*, 1963). These factors include precipitation, runoff, topography, vegetative cover, biological activity, and the inherent ability of a soil to resist erosion, i.e. its erodibility. Research has also identified wide seasonal variability in soil erosion patterns in some climates. For example, the majority of soil erosion and sediment transport in Southern Ontario watersheds occurs during the winter and spring months of March, April and May (Dickinson *et al.*, 1975; Dickinson & Wall, 1977). Although some of the factors noted above allow for such variability, and there have been qualitative linkages developed between observed erosion patterns and seasonal changes in precipitation, runoff, and vegetative cover, the role of soil erodibility in this regard is quite unclear. In fact, a method of measuring or indexing soil erodibility, let alone its possible variability in time has not yet been agreed upon.

Wischmeier *et al.* (1971) have related soil erodibility to soil texture, organic matter, a permeability index, and a soil structure index. Although their K factor provides a statistically validated and highly efficient index of erodibility, it does not allow for seasonal variation in soil conditions such as bulk density, soil water, or soil strength.

Many researchers, including Middleton (1930), Gerdel (1937), Peele *et al.* (1938), Anderson (1951), Andre & Anderson (1961), Woodridge (1964), Willen (1965) and Bryan (1968) have developed and explored a number of possible indices of soil erodibility based on soil properties affecting dispersion or dispersion and water transmission. Some of the more significant of these indices include dispersion ratio, erosion ratio, clay ratio, surface aggregation ratio, aggregate stability, and indices based on soil mechanical properties. Very few of these indices either allow for or have been related to seasonally-varying soil conditions.

The purpose of the present study has been to identify dynamic soil properties which may effect seasonal changes in soil erodibility in climates similar to that of Southern Ontario, and explain ways of indexing these properties such that they could be incorporated into a soil erodibility index. Two stages of the study have incorporated watershed and laboratory investigations.

LOCATION AND DESCRIPTION OF STUDY WATERSHEDS

Data from two drainage basins, Big Otter Creek and Big Creek, have been considered in the watershed portion of the study. These adjacent basins lie in the most southern part of Canada, centred at 42°51'N latitude and 80°36'W longitude. The location in Southern Ontario (shown in Fig.1) has a temperate climate which is moderately influenced by Lake Erie to the south. The watersheds have a relatively long frost-free period of 147 days per year, and an average annual precipitation of 957 mm distributed very uniformly throughout the year. The average annual temperature is 8.1°C, with the maximum monthly average of 21.2°C occurring in July and the minimum monthly average of -4.9°C occurring in January.

The Big Otter Creek basin has an approximate area of 712 km^2, with a length of 48 km in the north-south direction. The topography of the basin is dominated by two physiographic forms, the Mount Elgin Ridges and the Norfolk Sand Plains, both deposits of the last continental glacier that occupied the area (Chapman & Putnam, 1966). The morainic ridges cover the north and northwest part of the watershed, while the sand plains cover the south and southeast portion. The elevation of the drainage basin varies from 174 to 335 m above mean sea level.

Agriculture on the loam and silt loam textured soils of the end moraines includes primarily corn, with some grain, hay and pasture.

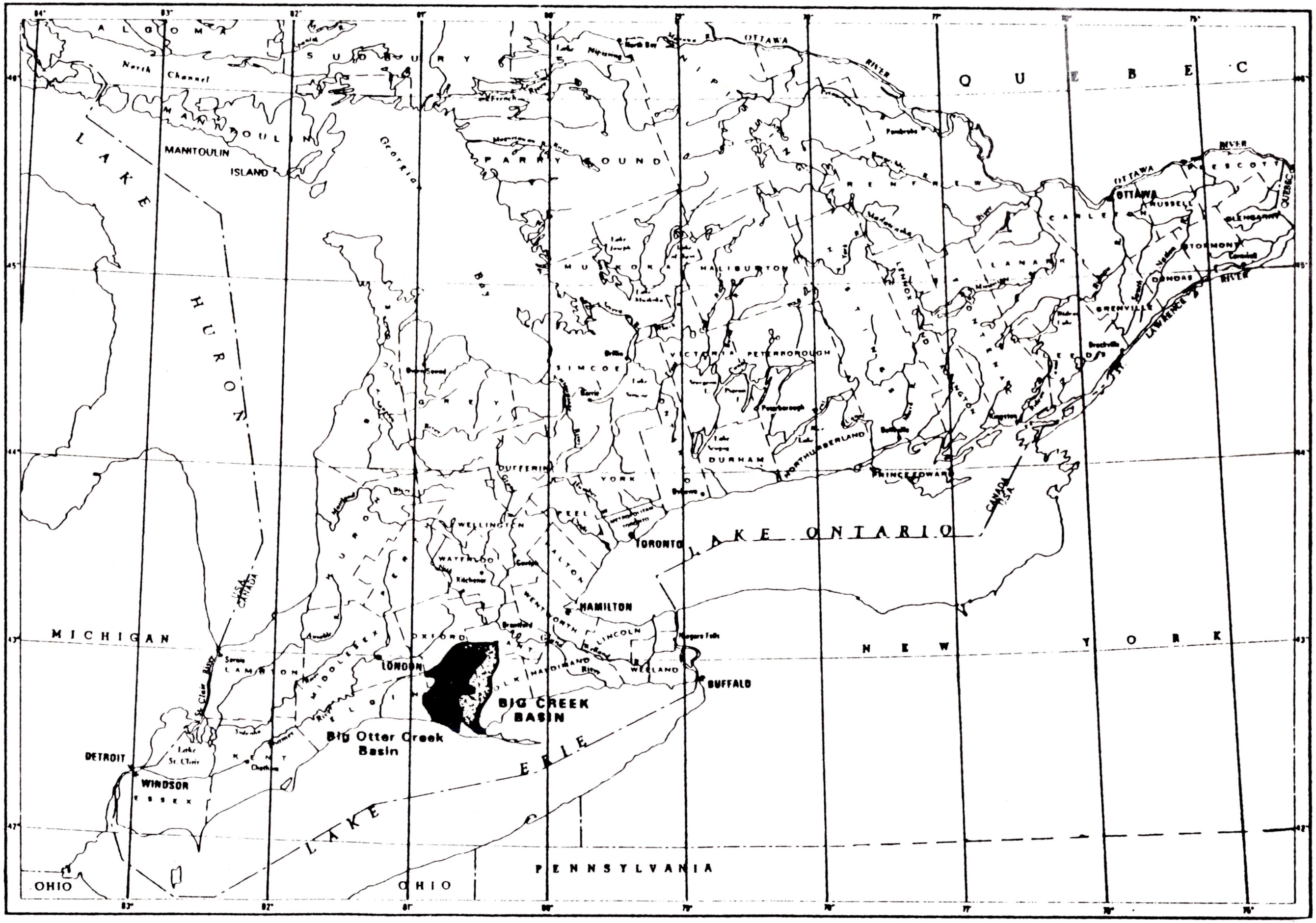

FIG.1 Location map of the Big Otter Creek and Big Creek study basins in Southern Ontario, Canada.

The corn is managed in larger field areas and cropped continuously. Tobacco is grown on the sands and loamy sands of the sand plains as a continuous crop or in rotation with grain (usually rye) or with corn as a market crop.

The Big Creek basin has an approximate area of 725 km^2, with a length of 56 km in the north-south direction and a width of 13 to 23 km. The topography is characterized by a broad, flat sand plain, interrupted sporadically by prominent beach ridges and deep stream valleys. In this basin, as in the Big Otter Creek basin, tobacco is the principle agricultural crop on the sandy soils of the plains.

WATERSHED PERSPECTIVE

The general structure of the watershed part of the study has involved an explanation of suspended sediment load events in relation to meteorological information regarding rainfall, snowmelt, and soil temperature. The sediment loads in each of the study basins have been used as qualitative indicators of the occurrence and the relative order of magnitude of soil erosion. As bank erosion has been determined not to comprise a major portion of the suspended load in the study basins, sediment events are justifiable indicators of erosion events. Since it is likely that the sediment transport factors from field to stream change from event to event, an event exhibiting a relatively large sediment load can be considered to indicate considerable erosion activity but a small sediment load event can indicate the occurrence of relatively little erosion or very limited transport of eroded material. Qualitative field observations in the study basins have confirmed that whenever widespread erosion has occurred, a sediment event of at least moderate magnitude has resulted. Storm situations causing very localized erosion activity have not led to noticeable sediment loads.

Since it is known that a large portion of the sediment loads in Southern Ontario are transported during winter and spring events (Dickinson & Wall, 1977; Wall *et al.*, 1979), attention in this study has been given to the 6 month period from November to April. Sediment event data were extracted for the years 1970 to 1977. Each event was categorized according to firstly, the nature of the precipitation and runoff at the time (i.e. only rainfall (R), only snowmelt (S), rainfall and snowmelt (RS), and unknown (U)), secondly, temperature conditions at the ground surface (i.e. frost (F) and no frost (NF)), and thirdly, temperature conditions between 5 and 20 cm below the ground surface (i.e. frost (F) and no frost (NF)). A display of the results from this analysis is presented in Table 1.

The following observations can be made from the tabulated results:

(a) Larger sediment loads and a greater number of sediment events occur in the Big Otter Creek basin, the basin with the larger percentage of morainic soils.

(b) Virtually all of the sediment events have resulted from rainfall or a combination of rainfall and snowmelt conditions. Very few events have been created by snowmelt alone.

(c) Most, if not all, sediment events observed in the study basins have occurred when the soil surface temperature has been above freezing. In fact, most of the events have occurred when the soil

TABLE 1 Sediment yield from significant events for the winter and spring period from two small watersheds in Southern Ontario, Canada

Drainage basin	Precipitation event type	Surface conditions	Number of sediment events	Mean load per event ($t\ km^{-2}$)	Subsurface conditions	Number of sediment events	Mean load per event ($t\ km^{-2}$)	Median load per event ($t\ km^{-2}$)
Big Otter Creek	R	F	2	8.6	F	1	3.9	-
					NF	1	13.3	-
		NF	17	27.8	F	5	39.1	39.1
					NF	12	23.1	8.6
	RS	F	2	5.9	F	2	5.9	-
					NF	-	-	-
		NF	20	25.1	F	13	32.4	34.4
					NF	7	11.5	6.6
	S	F	-	-	F	-	-	-
					NF	-	-	-
		NF	2	21.5	F	1	8.6	-
					NF	1	36.2	-
	U	F	2	8.8	F	2	8.8	-
					NF	-	-	-
		NF	-	-	F	-	-	-
					NF	-	-	-
Big Creek	R	F	-	-	F	-	-	-
					NF	-	-	-
		NF	7	7.0	F	3	9.8	-
					NF	4	5.0	-
	RS	F	-	-	F	-	-	-
					NF	-	-	-
		NF	5	12.5	F	4	12.5	-
					NF	1	12.9	
	S	F	-	-	F	-	-	-
					NF	-	-	-
		NF	1	5.5	F	1	5.5	-
					NF	-	-	-
	U	F	-	-	F	-	-	-
					NF	-	-	-
		NF	2	6.3	F	2	6.3	-
					NF	-	-	-

surface temperature has been between 0 and 5°C.

(d) The subsurface soil temperature conditions were quite variable during stream sediment events. Most of the events resulting from rainfall conditions alone exhibited no or very little frost in the ground; while most of the events occurring as a result of combined rainfall and snowmelt conditions showed evidence of one or more frost layers.

(e) There is some evidence that the most substantial sediment loads have occurred in the study basins firstly, as a result of rainfall or a combination of rainfall and snowmelt conditions, secondly, when the ground surface temperature is above freezing, and thirdly, when subsurface temperatures reveal the presence of frost layers.

The sediment events occurring under conditions when the soil surface was unfrozen but the subsurface soil was frozen were more common during the period late February to early April. During this period the frozen subsoil at a shallow depth usually resulted in a decrease in both infiltration rate and cumulative infiltration. These conditions helped to created a saturated to supersaturated soil-water matrix in the top soil Further, Kay (1979) found that the soil densities during this time of the year could be extremely low, as a result of earlier freeze-thaw cycles. The soil surface was very unstable under these conditions, and any disturbance at the surface caused by rainfall and/or runoff resulted in considerable detachment and transporation of soil particles.

Under unfrozen surface and subsurface conditions, the erosion process was more influenced by soil layering due to changes in soil density with depth. These conditions were common during the spring period and particularly during the month of April. The soil densities at the surface remained much lower than those of the subsurface (Kay, 1979). This condition created a temporary soil layering, with a relatively permeable low density and low strength soil overlaying less permeable higher density and high strength soil. These conditions restricted water flow into the subsoil and contributed to the supersaturation of the surface soil. Again the combination of low density surface soil at high moisture content proved to be highly erodible.

LABORATORY INVESTIGATION

In light of the qualitative evidence drawn from the field study, a preliminary laboratory investigation was designed to consider the nature of possible relationships between shear strength, soil water conditions, and soil density for four Southern Ontario soil textural classes. A sand, two silt loams, and a silty clay were examined, the sand and silt loam soils being present in the study basins.

A laboratory vane shear methodology (Youssef *et al.*, 1965) was used to determine the shear strength characteristics of remoulded samples of the selected soil textures. *In situ* vane shear strength was also evaluated in the field for the soil samples obtained from the study basins (McCormack & Wilding, 1979). Selected results from the laboratory experiments have been summarized in Fig.2, including fitted regression relationships.

The "break point" in the shear stress/water content relationships has been interpreted as an indication of water content at which the soil passes from a plastic into a liquid state, becoming considerably

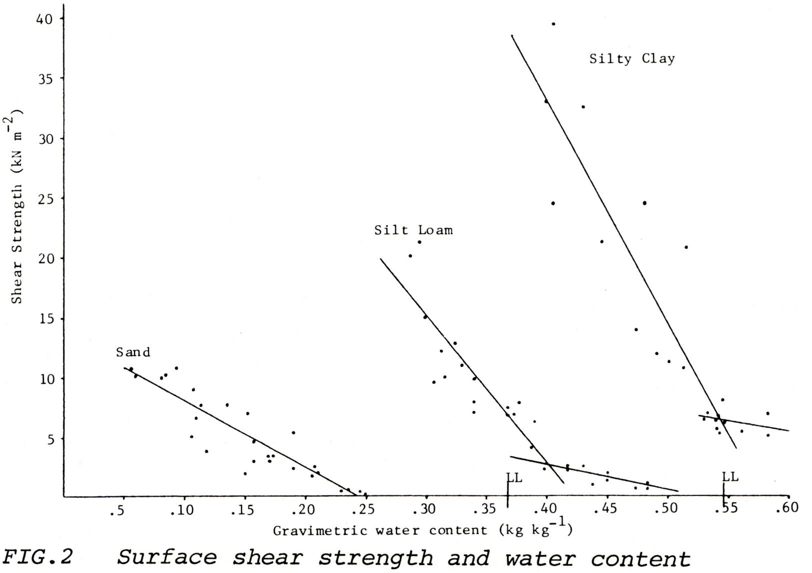

FIG.2 Surface shear strength and water content relationships for three Southern Ontario soils.

more susceptible to movement as a result of any applied force. The water content at the "break point", the slope of the relationship for water contents below that at the "break point", and the change in slope of a function on either side of this point have all been found to be a function of the clay content of the soil. A soil with a greater clay content exhibits a higher water content at the "break point"; and exhibits shear strength which approaches this point more rapidly and changes most abruptly at the "break point". Further, the "break point" occurs at a water content somewhat greater than that determined by traditional liquid limit techniques, the difference increasing with soil clay content. For each soil other than sand, the moisture content at saturation was determined to be in the vicinity of or somewhat below that of the "break point" identified in Fig.2, confirming that water contents much above these values would not normally be achieved under natural, slow wetting conditions. However, during spring thaw periods in Southern Ontario, water content in surface soils can be expected to be not only in the vicinity of but also in excess of that at the critical "break point".

Soil density also has been found to have a significant effect on the shear strength characteristics of the agricultural soils being studied. Preliminary results from field determinations are presented in Fig.3. Although the data to date are sparse at high water content, it is evident that the water content at which the soil shear strength approaches critically low values is considerably lower at lower soil densities. In other words, when the soil is less dense, low shear strength values can be achieved more readily with the addition of water. Again the vulnerability of surface soils of low density in the Southern Ontario spring period appears to be validated by the laboratory evidence.

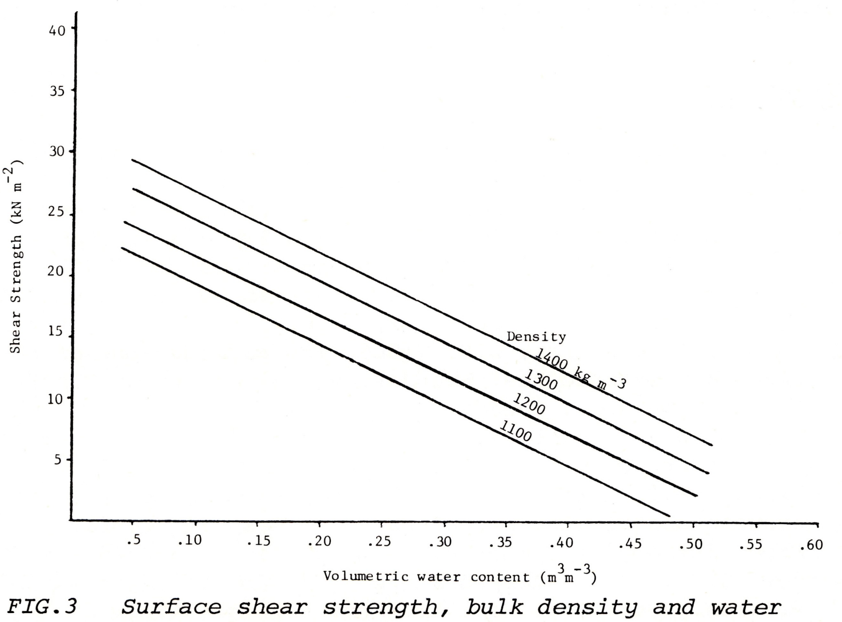

FIG.3 Surface shear strength, bulk density and water content of a Southern Ontario silt loam soil during spring 1981.

CLOSING COMMENTS

The preliminary field study discussed here has provided a useful perspective to focus attention on the apparent conditions surrounding principal erosion events, e.g. precipitation, soil surface temperature, and subsurface soil temperature. Further study of these situations has drawn attention to the possible significance of soil density and soil water content and to the manner in which these soil parameters become important. Soil shear strength may or may not be a key index of soil characterization for the purpose of describing soil erodibility. It is certainly more easily determined than many, but requires validation as a soil erosion index.

If surface soil shear strength or some index akin to it is found to be an important indicator for soil erosion, a number of fascinating hypotheses are provoked. For example, soil erodibility becomes a dynamic rather than a static characteristic. Seemingly quite different climatic conditions (e.g. a dry arid situation and wet spring thaw conditions) may both be highly susceptible to erosion due to the occurrence of low shear strength, the shear strength of very dry soil also approaching zero. The importance to erosion of low soil density situations may also be similar in differing climates, whether the density is lowered by freeze-thaw cycles, by biological activity, or by other means.

The picture is far from complete. Field data on soil characteristics during the period of relatively high erosion and sediment transport in Southern Ontario are still extremely sparse. Measured erosion rates are also badly needed for this period. Only when such information becomes available will it be possible to explore in detail the nature of relationships between soil erosion and soil shear characteristics or soil erosion and key dynamic soil characteristics.

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