Use of a submerged jet device to determine channel erodibility coefficients of selected soils of Mexico

K.N. Potter, J. de J. Velázquez-Garcia, and H.A. Torbert

ABSTRACT: More than half of Mexico's soil and water resources are considered moderately to severely degraded, primarily due to erosion and sedimentation. Characterization of soil susceptibility to erosion in the field is often hampered by difficulty in obtaining adequate water supplies. We tested a method to determine soil erodibility coefficients for concentrated water flow that had not been previously applied to agricultural soils. The submerged jet method of determining soil erodibility coefficients was tested on six soils in central Mexico of varying texture and predominant clay mineralogy near the end of the corn (*Zea mays* L.) growing season. The resulting erodibility coefficients generally segregated soils of similar texture and mineralogy. Soil silt plus very fine sand percentage and Plasticity Index were important soil properties affecting the Jet Index values. Moldboard plowed soils were more erodible at the end of the growing season than no-tilled soils at all sites except for two recent volcanic soils. The results of these tests, along with the relative ease of use and minimum labor and water requirements, suggest that the submerged jet device is a useful tool to determine soil erodibility coefficients of agricultural soils.

Keywords: Concentrated flow, erosion, submerged jet

Soil erosion by water is a serious problem in Mexico. Traditional agricultural practices are often cited as promoting accelerated erosion rates. Hillslope and gully erosion have been identified on 65 - 85% of the land as a result of deforestation and inappropriate cultivation of drylands (Bocco and Garcia-Oliva 1992). Water quality concerns are increasing due to erosion and concomitant sedimentation. Three hundred major watersheds in Mexico, with a total annual water yield of about 400 billion m^3 (523 billion yd^3), are considered degraded due to loss of vegetative cover, soil erosion, loss of nutrients, agrochemical pollution, and lake eutrophication (Albert 1996). Sedimentation and lake eutrophication have been detrimental to a local fishery in the Patzcuaro watershed and have caused the initiation of an intensive research and extension demonstration project in Mexico (Tiscareño-López et al. 1999).

In order to control or predict soil erosion by water, an understanding of the soil's susceptibility to erosion must be developed. Erosion by water is classified in two ways: as concentrated flow or sheet erosion. Erosion by concentrated flow describes the detachment and transport of soil by flowing water while sheet erosion describes soil detachment resulting from raindrop impact and overland flow of water. In agricultural areas, sheet erosion may be controlled by conservation tillage practices that promote leaving residue on the soil surface.

Rills, ephemeral gully, gully, and channel erosion are examples of concentrated flow erosion. Erosion from concentrated flow is usually expressed by:

$$\varepsilon_r = K_d\ (\tau - \tau_c) \tag{1}$$

where:

ε_r = the erosion rate, (cm hr),
τ_c = a critical stress, (Pa)
τ = the local effective stress, (Pa)
K_d = the soil erodibility coefficient, (cm hr^{-1} Pa^{-1}).

The critical stress, τ_c, has proven very difficult to quantify on cohesive soils; the literature reports large ranges. King et al. (1995), using rainfall simulation methods on artificially formed rills, found that τ_c varied more as a function of residue than of soil properties or management. Several researchers have suggested that for channels with highly non uniform flow, the stress that causes a particular erosion rate may be more appropriate (Lavelle and Mofjeld 1987; Hanson 1990a). Hanson (1990a) evaluated channel erosion based on the expression

$$\varepsilon_r = K_d\ (\tau) \tag{2}$$

There is a great deal of potential in a device that can be used to determine the erodibility of different soils and management systems, as well as possible changes in erodibility values according to seasonal differences. Previous procedures to quantify erodibility coefficients have included large and small flumes, circular tanks and impellers, annular channel, and a rotating viscometer (Hollick 1976). Some methods require small, remolded samples, which allow for more control in the laboratory but ignore the possible effects of sample size and surface morphology that can influence the results. In most cases, *in situ* testing is advocated as a check of the laboratory results. However, most *in situ* checks are not conducted, as they are generally complex, relatively costly, and require large amounts of water and personnel to complete.

Because of these limitations, attempts have been made to find a simpler method or a substitute for calculating the erodibility coefficient. Several authors have proposed using the Universal Soil Loss Equation (USLE) "K" factor as a first approximation of the K_d coefficient (Dickinson and Scott 1979; USDA 1980). But experimentation has shown that use of the USLE "K" factor results in poor estimates of concentrated flow erosion (Zhu et al. 1995). Laflen et al. (1991) also found that rill erodibility was poorly correlated with the USLE "K" factor.

Hanson (1990b) designed and tested a submerged jet device to characterize soil

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Reprinted from the *Journal of Soil and Water Conservation*
Volume 57, Number 5

properties and to evaluate their performance in reservoir spillways (ASTM 1995). The submerged jet device, based on scour theory (Hanson 1990b), resulted in a parameter known as the Jet Index, which is an estimate of the change in scour depth per unit of time for a given water velocity. The Jet Index was calibrated against erosion coefficients (K_d) developed by open channel testing of the same soils, which had a wide range of soil properties (Hanson 1990b). The resulting empirical equation related the Jet Index to soil erodibility coefficients derived by open channel testing.

Only a few applications of the submerged jet device have been reported. Hanson (1991) used it to estimate channel erosion in compacted reservoir spillways and Allen et al. (1997) used it to estimate streambed erosion in consolidated materials. Allen et al. (1997) also used a modified submerged jet system to estimate K_d values for stream channel erosion in central Texas. When used in a hydrologic simulation model, the resulting K_d values provided good estimates of downcutting (Allen et al. 1999).

The submerged jet device, as modified by Allen et al. (1997), is also easily portable, labor efficient, water conservative, may be used *in situ*, and has a low cost of construction. While the characteristics of the submerged jet device suggest it may also be useful for determining K_d values for agricultural soils, no *in situ* applications of the submerged jet device to agricultural soils have been reported.

The objective of this study was to test the submerged jet device as a means to determine the relative erodibility of selected important agricultural soils. Soils were selected in central Mexico with a range of characteristics that were different from the materials reported in previous submerged jet studies.

Methods and Materials

The submerged jet device. A vertical, submerged jet device was constructed and used to determine soil erodibility for selected soils in central Mexico. Figure 1 illustrates the device in use.

The submerged jet device followed closely the design of Hanson (1990b) as modified by Allen et al. (1997). The base ring flange [7.5 cm (3 in)] is driven into the soil and the ring [48 cm (19 in) outside diameter, 42.5 cm (16.75 in) diameter center opening] leveled. A rubber gasket is placed on the ring. The cylindrical tank is attached to the base ring with six bolts and tightened sufficiently to prevent leakage. The cylindrical tank consists of an outer and inner cylinder that is separated by about 1 cm (0.4 in). The inner cylinder is raised 10 cm (4 in) above the lower edge of the outer cylinder to allow drainage and to serve as a baffle to minimize return turbulence to the jet.

The standpipe, which supplies water to the jet, consists of a 2.3 m (7.5 ft) long by 0.051 m (2 in) diameter PVC tube. The lower portion of the PVC tube is fitted with a 0.635 cm (.25 in) inside diameter jet nozzle. The standpipe has three overflow ports to provide a range in the head of water, resulting in three jet velocities. The standpipe is mounted in a support that rests on the inner liner and was adjusted so that the tip of the nozzle was 10.5 cm (4.13 in) above the soil surface.

The standpipe was then removed and replaced with a lid that attached to the tank in a position that remained consistent for each measurement. The lid had a central hole that provided a reference point from which to measure the distance from the lid to the soil that would be disturbed by the water jet. A single metal rod [3 mm (.13 in) in diameter and 50 cm (20 in)long] was used to measure the distance from the lid top to the soil surface. A plastic liner was placed upon the soil surface to prevent surface erosion and the tank was filled with water to a depth of about 0.25 m (10 in). The plastic liner was removed and the standpipe replaced, submerging the nozzle tip in the water. Water was supplied to the standpipe [with a 0.25 kW (1/3 hp) pump] to start a run. A constant head was maintained by insuring water continuously overflowed from the appropriate outlet port. At three 10 min time increments water flow to the standpipe was stopped, the jet was removed, and the depth of maximum scour determined. After completing a run, the tank was drained and reinstalled at an adjacent location to repeat the procedure with a different energy level. Three separate jet velocity tests were run for each treatment. The jet velocities (U_0) were predetermined to be 301, 464, and 556 cm s^{-1} (9.9, 15.2, and 18.2 ft s^{-1}).

Figure 1

The submerged jet apparatus set up for a test.

Locations. Six locations were selected for study in the states of Michoacan and Jalisco in central Mexico (Figure 2). These sites provide a range of soil properties that may influence erodibility. Bulk surface samples [0 - 15 cm (0 - 6 in)] were collected and soil characterization tests performed by the Natural Resources Conservation Service-Soil Survey Laboratory (NRCS-SSL) to determine soil texture (pipette method), predominant mineralogy (X-ray diffraction), and carbon content (Leco SC-444 Carbon Analyzer) (National Soil Survey Center 1996). Soil bulk density and water content at the time of the submerged jet runs were determined from 4.01 cm (1.58 in) diameter soil cores for the surface 10 cm (4 in) of the soil. Locations and soil characterization properties are presented in Table 1. Surface soil bulk density and water content are presented in Table 2.

Long-term management studies are being conducted at the sites to determine management effects on continuous corn (*Zea mays* L.) yield and soil erosion. The management systems chosen for this study were conventional moldboard plowing and no-till with all corn residues retained on the soil surface. The fields had been under continuous management for a minimum of four years. The submerged jet runs were conducted in November 1999 on non-trafficked inter-row areas near the end of the growing season. The study sites were leveled and all surface residues removed from the jet impact site before conducting the run. Depth-of-scour data was collected three times at 10 min increments at each of three energy levels for each soil-management combination with the exception of the Guzman site, where runs were restricted to 8 min intervals due to a

Figure 2

Location of the study sites.

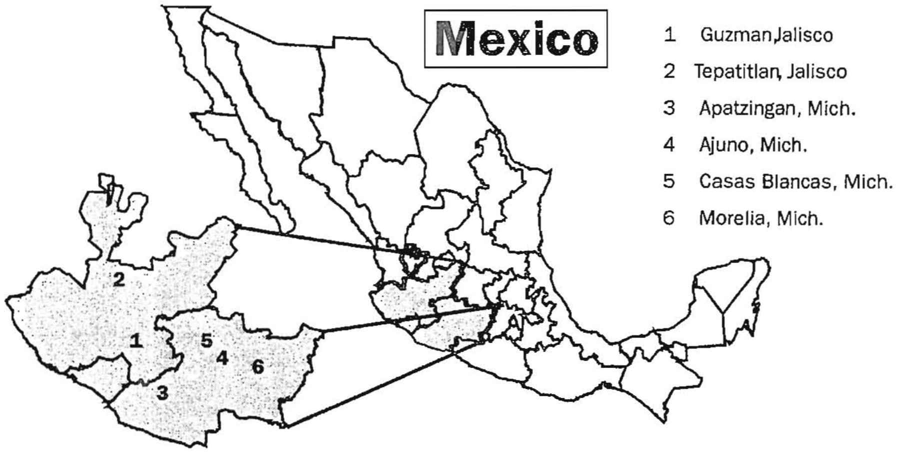


Table 1. Selected properties for six soils in central Mexico.

Site	Clay $(\%<2\mu)$	Sand $(0.05>\%<2mm)$	Textural classification	Predominate clay mineralogy[†]	pH[±]	C $(kg\ kg^{-1})$	Liquid limit	Plastic limit
Guzman	12.3	63.2	Sandy loam	FD3	5.5	0.010	23	3
Ajuno	12.2	48.7	Loam	KK1	5.5	0.020	73	6
Casas Blancas	16.1	25.5	Silt loam	NX6	5.3	0.073	80	12
Tepatitlan	47.1	13.1	Clay	KK2, HE2	5.6	0.018	38	16
Apatzingan	58.9	21.7	Clay	MT4	7.8	0.012	90	58
Morelia	77.4	0.6	Clay	CR2, MT2	6.7	0.016	81	49

[†] **MT = montmorillonite, FD = feldspar, CR = cristobalite, NX = non-crystaline, KK = kaolinite, HE = hematite. The number refers to relative peak size: 1 = very small, 2 = small, 3 = medium, 4 = large, 6 = no peak.**

[±] **pH is 1:1 H_2O paste.**

shortage of available water.

Data from all energy levels within a soil-management combination were combined for interpretation. Data analysis consisted of calculating the Jet Index (Ji) as defined by Hanson (1990b), where the scour depth (cm) time $(s)^{-1}$ is plotted as the dependent variable versus a velocity function. The velocity function was defined as jet velocity multiplied by time (s) to the -0.931 power (i.e. $U_0\ t^{-0.931}$). The Jet Index, determined by least squares fit of the data, is the slope of the line with the intercept equal to zero (ASTM 1995). The erodibility coefficient, K_d, was then estimated based on Hanson's (1991) empirical equation:

$$K_d = 0.003\ e^{385Ji} \qquad (3)$$

where:

K_d = erodibility coefficient $cm^3\ (N\text{-}s)^{-1}$ and

Ji = Jet Index

A homogeneity-of-regression method was used to determine statistical differences in the Jet Index among soils and between conventional and no-till management practices within locations (Steel and Torrie 1980).

The homogeneity-of-regression method uses Student's t-test to test if slopes between treatment pairs are measurably different, considering the variability in the data used for the regression. A stepwise regression procedure was used to relate the Jet Index values obtained to selected soil properties (SAS 1985).

Results and Discussion

The selected soils differed in soil properties that may affect the soil erodibility estimates. Soils at Morelia, Apatzingan, and Tepatitlan are high in clay content (Table 1). The Morelia and Apatzingan location soils are both vertic clay soils with montmorillonite being the predominate clay mineral. At the Tepatitlan site, the soil mineralogy is predominately kaolinite and hematite, both non-expansive clays. The Guzman, Ajuno, and Casas Blancas sites are coarser textured. The Guzman site clays are predominantly

Table 2. Surface (0 to 10 centimeters) bulk density and soil water content at the time of measurements.

Location	Treatment	Bulk density	Water content
		$(Mg\ m^{-3})$	$(kg\ kg^{-1})$
Guzman	Tilled	1.41	0.05
	No-till	1.31	0.07
Ajuno	Tilled	0.57	0.50
	No-till	0.38	0.62
Casas Blancas	Tilled	0.65	0.65
	No-till	0.51	0.76
Tepatitlan	Tilled	1.08	0.13
	No-till	1.07	0.14
Apatzingan	Tilled	1.17	0.24
	No-till	1.06	0.25
Morelia	Tilled	0.85	0.25
	No-till	0.87	0.28

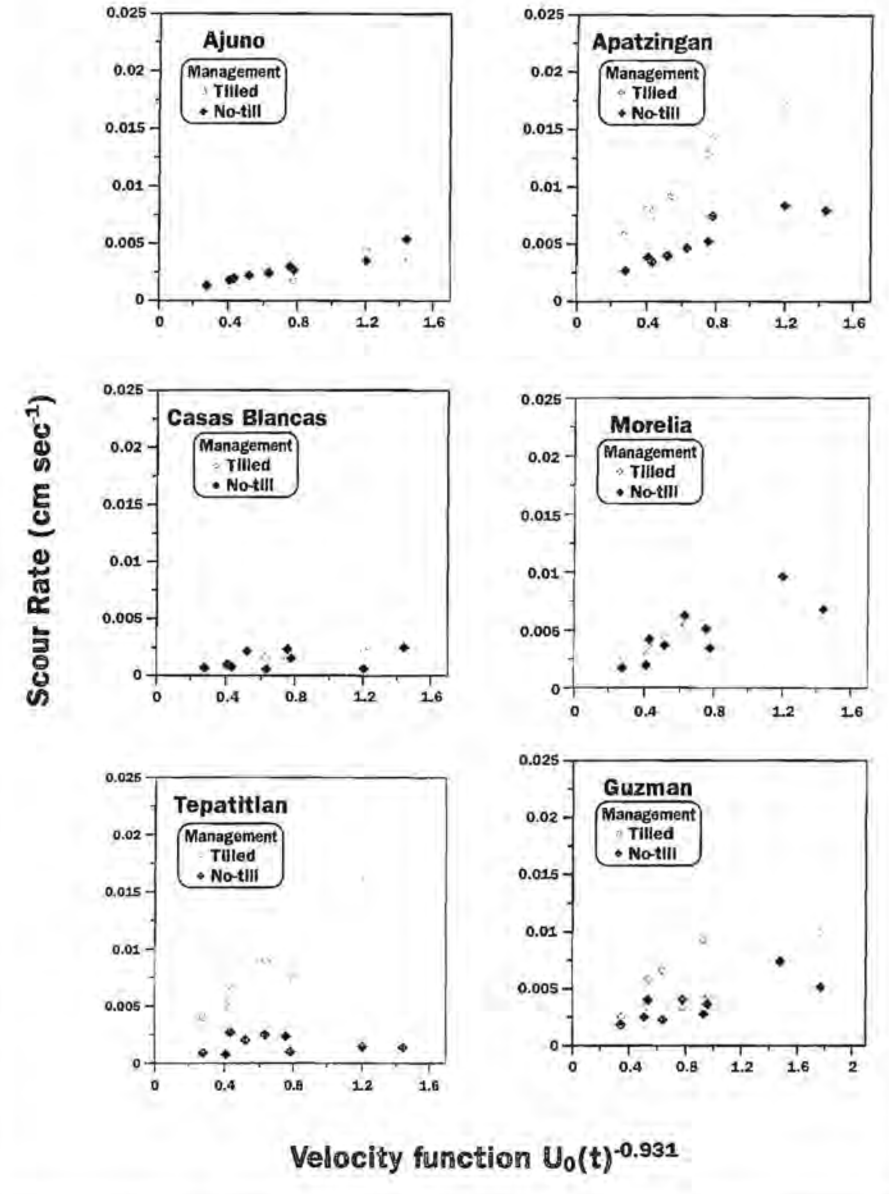
feldspars. The clay materials at the Ajuno and Casas Blancas locations are predominately amorphous. There was a small indication of kaolinite at the Ajuno location. The Ajuno and Casas Blancas locations are recent volcanic soils, which explains the low bulk density values found at these locations (Table 2) (Buol et al. 1973).

Depth of scour per unit of time was plotted against the velocity function for each soil-management combination (Figure 3). The slope of the least-squared-fit line with the intercept equal to zero is defined as the Jet Index. Low Jet Index values imply little change in surface elevation, or small amounts of scour, and a soil relatively resistant to erosion. A larger Jet Index value, in contrast, implies a more erosive soil or soil condition. Jet Index values ranged from a minimum of 0.00166 in the no-till soil at Casas Blancas to a maximum of 0.0164 in the tilled soil at Apatzingan (Table 3). Significant differences ($P<0.10$) in the Jet Index occurred between the tilled and no-till soils at all locations except for Ajuno and Casas Blancas, the recent volcanic soils (Table 3). Where differences in Jet Index were significant, the tilled soil had a larger Jet Index value than the no-till soil. This was probably caused by the tillage breaking aggregates near the surface, resulting in a more erodible condition. Also, the no-till sites had greater soil carbon contents near the surface than the tilled sites (Potter et al. 2001), which may have increased aggregate stability and resulted in lower Jet Index values in the no-till treatments. Regardless of the mechanism, the no-till soils were found to be less erosive than the tilled soils without even considering the effect of retaining residue on the surface of the no-till soils.

The no-till treatment was chosen for homogeneity-of-regression t-test comparisons among soils because the consolidated no-till soils were more representative of the soil properties than the tilled soils. The Jet Index values ranked the no-till soils in order of decreasing erodibility: Apatzingan ≥ Morelia > Guzman > Ajuno > Tepatitlan > Casas Blancas (Table 3). It is interesting to note that the Jet Indices were similar for the two montmorillonite-dominated clay soils at Apatzingan and Morelia, while the kaolinite-dominated clay soil at Tepatitlan was quite different. The large montmorillonitic clay content at the Apatzingan and Morelia sites resulted in self-mulching of the surface, a condition where small, low density soil aggregates form at the surface. Similar surface conditions have been reported with cracking clay Vertisols that also have been found to be highly erosive (Potter et al. 1995). In these soils, the cohesion forces between aggregates were weak and aggregate detachment required less energy than with the consolidated non-expansive clay soil surface at Tepatitlan.

Figure 3

Depth of scour per unit of time plotted against the velocity function for six soils and no-till and tilled management treatments.



The effects of soil properties on the Jet Index were assessed using a stepwise regression procedure with the Jet Index as the dependent variable and selected soil properties as the independent variable (Table 5). Soil properties considered included bulk density, textural properties, organic carbon content, and Atterburg properties. Textural properties included percent sand, silt, clay, and silt plus very fine sand. Atterburg properties included the Liquid Limit, Plastic Limit, and Plasticity Index, which is the difference between the Liquid Limit and Plastic Limit. Only two parameters were retained in the regression equation at the F-test value less than the 0.15

Table 3. Jet Index and soil erodibility (K_d) coefficient values for six soils and homogeneity-of-regression analysis results for Jet Index comparisons between management systems within sites.

Location	Treatment	Jet index	K_d
			$cm^3 (N\text{-}s)^{-1}$
Guzman	Tilled	0.00750	0.054
	No-till	0.00395	0.014
	P > t†	0.02	
Ajuno	Tilled	0.00307	0.010
	No-till	0.00361	0.012
	P > t	0.92	
Casas Blancas	Tilled	0.00171	0.006
	No-till	0.00166	0.006
	P > t	0.17	
Tepatitlan	Tilled	0.01276	0.41
	No-till	0.00183	0.006
	P > t	<0.001	
Apatzingan	Tilled	0.01638	1.66
	No-till	0.00692	0.043
	P > t	<0.001	
Morelia	Tilled	0.00739	0.052
	No-till	0.00634	0.034
	P > t	0.10	

† **Probability of a greater Student's homogeneity-of-regression t-test value between tilled and no-till management systems within a location. A probability ≤ 0.10 was considered significant.**

Table 4. Results of homogeneity-of-regression t-tests between no-till soils at all site combinations.

	Ajuno	Casas Blancas	Tepatitlan	Apatzingan	Morelia
	(P > t)†				
Guzman	0.31	0.18	0.31	0.001	0.01
Ajuno		0.05	<0.001	0.05	0.01
Casas Blancas			0.04	0.001	<0.001
Tepatitlan				<0.001	<0.001
Apatzingan					0.35

† **Probability of a greater Student's homogeneity-of-regression t-test value with no-till management systems between location pairs.**

Table 5. A regression model comparing no-till Jet Index values and selected soil variables†. The model was generated using a step-wise procedure with parameter retention minimum (P>F= 0.15).

Variable	Parameter estimate	Partial R^2
Intercept	0.00846	
% Silt + % Very Fine Sand	-0.000155	0.795
Plasticity Index	0.000052	0.143
Total Model		0.938

† **Variables tested included bulk density, % clay, % silt, % sand, % silt + % very fine sand, % carbon, Plastic Limit, Liquid Limit, and Plasticity Index.**

probability level. The percent silt plus very fine sand parameter accounted for 79.5% of the variability in the no-till Jet Index values. Addition of the Plasticity Index to the regression equation accounted for an additional 14.3% of the Jet Index variability. Both parameters have been used to predict soil erodibility in other models. Wischmeier and Smith (USDA 1978) proposed using silt plus very fine sand content as the first parameter in a nomograph to estimate a soil erodibility parameter for the USLE. Allen et al. (1999) found the Plasticity Index to be an important parameter in estimating the Jet Index values of stream channels. The Plasticity Index is related to the amount and mineralogy of the soil clay fraction (Spangler and Handy 1982).

Soil erodibility values (K_d) calculated using Hanson's (1991) equation (Equation 3), ranged from 0.006 $cm^3 (N\text{-}s)^{-1}$ at Tepatitlan and Casas Blancas to 1.66 $cm^3 (N\text{-}s)^{-1}$ in tilled soils at Apatzingan (Table 3). Some of the K_d values reported in this study are outside the range of the K_d values of the soils Hanson (1991) used in developing Equation 3. Further testing may be needed to determine if Equation 3 is still valid in this range of values.

Summary and Conclusion

The submerged jet device was used to estimate soil erodibility on agricultural soils at six sites in central Mexico. Soil properties appear to affect the submerged jet results in the same manner as results obtained by other methods. Silt plus very fine sand content and the soil Plasticity Index were found to affect Jet Index values across a wide range of soil textures and clay mineralogy. The effect of no-till management was differentiated from moldboard plow systems in four of the six locations. But management effects were not clearly associated with soil properties. This may have been because measurements were made at the end of the growing season when differences between management systems may be expected to be the least because of consolidation and settling from rainfall.

The submerged jet is an inexpensive, simple device that allows rapid *in situ* estimation of concentrated flow erosion coefficients. The device has relatively low water and labor requirements, which is especially advantageous in areas without a readily available water supply. The ease of use may allow more frequent determinations to estimate seasonal variability and improved understanding of the effect of tillage practices on soil erodibility.

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