Imhoff Cone Determination of Sediment in Irrigation Runoff

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ABSTRACT

There is a need to rapidly quantify erosion from irrigated farmland. The prevailing method consists of collecting runoff samples, then filtering, drying, and weighing them to determine sediment concentration. Labor cost and slow data availability prompted development of a faster, less expensive technique. Sediment settling volume in a graduated vessel was expected to correlate well with total mass of suspended sediment. Eight soils varying in texture, mineralogy, and organic-matter content were sampled, fragmented, and air dried. A series of 1-L suspensions was prepared with sediment concentrations from 1 to 30 g L^{-1}. Samples were either hand shaken for 30 s or mechanically blended for 60 s. Suspensions were decanted into graduated Imhoff cones and allowed to settle for 0.5 h (1800 s). The series was repeated three times for each soil. Settling volume was regressed against sediment concentration (total sediment, g L^{-1}). Field calibrations for two soils were developed from furrow runoff samples. Laboratory regressions had a mean r^2 of 0.99. Field regressions of two soils had r^2 of 0.94 or higher. Cone design did not permit accurate volume estimates of the first 1 mL, causing slopes and intercepts to very among field regressions for sediment concentrations <1.0 g L^{-1}. These samples, however, represent negligible erosion, and therefore have little value. Slope and intercept of field regressions corresponded closely to 30-s-shaken laboratory regressions but different statistically at $P \leq 0.05$. The technique provided a rapid, inexpensive, and accurate suspended-sediment determination in the field for concentrations >1.0 g L^{-1}. Several settling-volume predictions based on textural components and organic-matter content had r^2 >0.60. Laboratory 30-s hand-shaken calibrations may be adequate for diagnostic purposes, but individual field calibrations should be performed for research purposes.

EROSION from irrigated farmland has been identified as a serious environmental problem requiring expanded research (Hajek et al., 1990). Surface-irrigated land in the USA exceeds 13.6 million ha, 57% of total land irrigated (Anonymous, 1991). Despite management to minimize soil loss, furrow irrigation systems are inherently erosive on many soils. Where soils lack significant structure or durable aggregates, or are low in organic matter, furrow erosion can exceed soil-loss tolerance levels even on low slopes. There are 1.3 million surface-irrigated hectares in the Pacific Northwest on such soils (Anonymous, 1991). Erosion commonly removes 5 to 50 t ha^{-1} yr^{-1} and much of it occuring near furrow inlets (Berg and Carter, 1980; Kemper et al., 1985; Fornstrom and Borelli, 1984). Sediment concentrations in irrigation return flows in southern Idaho have ranged from 0.02 to 15 g L^{-1}, and are often the largest single pollutant of surface drainage waters (Brown et al., 1974, 1981).

Most studies have relied on variations of the Total Suspended Matter (Nonfiltrable Residue) Method no. 224C (Taras et al., 1971) to determine the amount of suspended sediment in water samples. This method involves preweighing of filter paper, sample storage after collection, slow filtering of suspended sediments, oven drying of filter paper and sediments, and reweighing of the oven-dry filter paper with sediment. Generally, this process requires 0.5 to 1.0 h of laboratory time to process each sample. As a practical limit, it takes about 1 wk to collect, process, and obtain data for 100 samples. This imposes a serious logistical and economic limit to sediment-concentration monitoring in an intensive study of erosion from irrigated fields.

Turbidity determination has been explored as a rapid indirect indicator of suspended sediments, but it related accurately to suspended sediments for only a narrow soil particle-size range (King et al., 1978). Also, turbidity measurements are useless when sediment loads are heavy, and rapid settling of large portions of the suspended sediment occurs.

Various simplified mass–volume relationships were explored to quantify suspended sediment more rapidly. All required making certain assumptions regarding suspension and particle densities, or use of hydrometer to determine their values. These approaches were abandoned because they still required sample collection, storage, and tedious laboratory procedures, ultimately saving no time.

The Imhoff cone has been used in the Settleable matter Method no. 224F (Taras et al., 1971) for sewage-sludge monitoring. A variation of the technique was used to estimate erosion from a limited number of fields of Kennewick silt loam (coarse-silty, mixed [calcareous]), mesic Xeric Torriorthent) in central Washington (van Nieuwkoop, 1979). Its suitability for use with four soils ranging from loam to loamy sand in texture (soil series not identified) in the Yakima and Columbia basins was studied and was related to Stoke's Law (Stice, 1982). Stice concluded that Imhoff cone settling volume could be statistically correlated with sediment concentration, but could not be successfully modeled because of the unpredictability of particle interactions affecting flocculation and aggregation in a model based on primary particle distribution. His regressions of Imhoff-cone volume vs. sample sediment concentrations of 0.25-h settling intervals provided r^2 values ranging from 0.65 to 0.99. Our preliminary assessment showed that, with Method no. 224F, most suspended sediment settled out of suspension in 0.25 to 0.50 h, regardless of soil texture. Even for clayey soil, settling was fairly rapid, since most of the suspension occurred as aggregates rather than individual primary particles. Furthermore, the amount of additional soil settling out of suspension from 0.5 to 1.0 h was negligible (1–2%), and caused no serious errors if a 0.50-h settling interval was inadvertently exceeded (D.L. Carter, 1981, unpublished data). Sediment remaining in suspension after 0.50 h is the nonaggregated clay fraction (Gee and Bauder, 1986), which does not settle rapidly.

To date, adaptation of Method no. 224F has neither been widely applied outside the Pacific Northwest nor tested on diverse soil taxa or textures. Magnitudes of

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Table 1. Selected physical characteristics of soils compared in the laboratory by Imhoff-cone and filtering methods.

Soil series	Taxonomic classification	Origin (state)	Particle-size distribution			Clay type	Organic matter†	Sample size range‡	
			sand	silt	clay			shaken	blended
			%				%	g	
Barnes loam	fine-loamy, mixed Udic Haploboroll	MN	49	34	17	2:1	3.41	3.0–23.0	1.9–21.4
Cecil sandy loam	clayey, kaolinitic, thermic Typic Kanhapludult	GA	64	18	19	1:1	1.25	2.5–28.2	3.1–28.2
Holtville silty clay	clayey over loamy, montmorillonitic (calcareous), hyperthermic Typic Torrifluvent	CA	4	35	60	2:1	0.64	1.7–21.5	2.3–21.2
Palouse silt loam	fine-silty, mixed, mesic Pachic Ultic Haploxeroll	WA	12	60	28	2:1	2.05	1.5–16.2	1.3–18.1
Portneuf silt loam	coarse-silty, mixed, mesic Durixerollic Calciorthid	ID	16	72	13	2:1	1.17	2.4–28.0	2.2–33.1
Sagehill fine sandy loam	coarse-loamy, mixed, mesic Xerollic Camborthid	OR	19	57	24	2:1	1.50	1.4–22.3	2.1–20.2
Sharpsburg silty clay loam	fine, montmorillonitic, mesic Typic Argiudoll	NB	5	49	46	2:1	2.26	1.7–23.2	1.6–20.9
Sverdrup loamy sand	sandy, mixed Udic Haploboroll	MN	73	13	14	2:1	2.12	3.8–31.6	4.0–30.7

† As estimated from organic-C content using the Van Bemmelen 1.724 factor.
‡ Scooped soil sample sizes varied in amounts within the range shown.

field-induced sources of error related to factors such as cultural practices has not been estimated. The objectives of this study were : (i) test the linearity and reliability of Imhoff-cone settling volumes as an accurate predictor of suspension sediment concentration of furrow-irrigation runoff samples; (ii) determine the likely range of variability in field calibration by comparing two levels of sample agitation in the laboratory; (iii) compare laboratory-derived and field-derived volume calibrations for predicting sediment concentrations; and (iv) estimate the likely calibration deviation induced by factors affecting runoff from furrow-irrigated fields.

MATERIALS AND METHODS

Laboratory Studies

Eight diverse soils (Table 1) were collected as described Lehrsch et al. (1991), gently fragmented by hand, and air dried without sieving. Soil textures were analyzed using the method of Gee and Bauder (1986). Soil organic matter was determined using the Walkley-Black procedure (Nelson and Sommers, 1982) for organic C and estimating organic matter using the Van Bemmelen factor of 1.724 to convert organic C content to organic-matter content (Jackson, 1958, pp. 205–226).

Using a graded series of four scoop sizes ranging from 2 to 25 mL, paired subsamples of each soil were deposited in 0.8 to 0.9 L of distilled water (leaving room in the container for rinsing during volume transfer and shaking). Each soil suspension was then either hand shaken by repeatedly inverting the sample about once per second for 30 s in a stoppered Erlenmeyer flask, or mechanically blended for 60 s in a Waring blender[1]. After agitation, suspended samples were decanted with rinsing and brought to 1.0-L volume in Imhoff cones. After allowing settling for 0.5 h, the volume of settled sediment was read from the Imhoff cones. Reading the volume of settled sediment sometimes required gentle leveling of the surface of the settled sediment in the Imhoff cones. This was easily accomplished with one or two gentle finger taps at the bottom of the cone. The entire contents of the Imhoff cones were then decanted, with rinsing, onto preweighed Whatman no. 50 (hardened) filter paper on large Büchner funnels. Water was removed under vacuum. Filter papers were carefully removed, dried at 105 °C overnight, and reweighed to determine sediment weight. This process was completed three times for each soil. Imhoff-cone volume of settled sediment at 0.5 h was regressed for a given agitation treatment for each soil against the total weight of soil initially added.

Mass of soil contained in 1 L of suspension was treated as the independent variable, with Imhoff-cone settling volume at 0.5 h the dependent variable. This approach was taken because the Imhoff-cone volume for a given mass of soil in suspension could vary, whereas, assuming no loss of sediment in the filtering process, the mass of soil suspended was an absolute parameter for each sample. In practice, once a given calibration has been established, the calibration equation would be solved for concentration (g L^{-1}) as the dependent variable, estimated from settling volume.

Field Studies

Laboratory calibrations were compared with field-derived calibrations for the Portneuf and Holtville soils during the summer and fall of 1989 and 1990 at Kimberly, ID, and Brawley, CA, respectively. Field calibrations for the Portneuf soil were obtained during two growing seasons. Calibration samples were taken from a field study in which runoff samples were collected separately from trafficked or nontrafficked furrows. Furrow outflow was sampled from fields equipped with small v-notched flumes. One-liter samples of free-flowing runoff were collected with 0.2 L styrofoam cups in 0.1 to 0.2-L increments from the discharge ends of the flumes and immediately tranferred into Imhoff cones. Cones were scored with a ring at the 1.0-L mark for leveling, and were placed on stands in the field adjacent to flume positions. The 0.5-h settling volume in the Imhoff cones was noted and samples were recanted into storage containers and carried to the lab, where sediments were determined using Method no. 224C (Taras et al., 1971). No attempt was made to compensate for fluctuations in suspension temperatures in the field. Field cone readings were regressed against filter-paper (Method no. 224C) mass

[1] Mention of trademarks, proprietary products, or vendors does not constitute a guarantee or warranty of the product by the USDA or the Idaho Agric. Exp. Stn., and does not imply its approval to the exclusion of other products or vendors that may also be suitable.

Table 2. Linear correlation, r^2, values resulting from regressing the slope of either the manually shaken or blended laboratory calibration on their difference for each of eight soils vs. soil property components of the individual soils.†

Mixing method	Soil property components‡												
	S	Si	C	S + Si	S + C	Si + C	OM	S × OM	Si × OM	C × OM	(S + Si) × OM	(S + C) × OM	(Si + C) × OM
	r^2												
Manually shaken	0.55	0.23	0.36	0.36	0.25	0.54	0.13	0.46	0.02	0.08	0.28	0.29	0.04
Mechanically blended	0.67	0.12	0.78	0.77	0.14	0.66	0.29	0.61	0.00	0.07	0.52	0.42	0.01
Slope difference	0.74	0.22	0.21	0.64	0.24	0.73	0.24	0.64	0.00	0.09	0.46	0.42	0.03

† The equation form is $y = ax + b$, where y is the slope of the manually shaken calibration, the mechanically blended calibration, or their difference, and x is the soil property or combination of soil properties.

‡ S, Si, C, and OM refer to percentage sand, silt, clay, or organic matter, respectively.

determinations. Field calibrations were compared over time to identify changes caused by cultivation, irrigation, etc. Field calibrations were also compared with laboratory calibrations to determine the feasibility of using a laboratory calibration for field diagnostic purposes.

The same approach was used to field calibrate the Holtville soil, with the source of sample variation being initial runoff from standard furrow irrigation vs. initial runoff of successive surge irrigations. One aspect of the field vs. laboratory comparison that differed between studies of the Portneuf and Holtville soils related to water quality. All laboratory calibrations were conducted with distilled water. The irrigation water used for the field calibration of the Portneuf soil was low in salts and Na. The irrigation water used for the field calibration of the Holtville soil was higher in total salts and Na. Typical analysis of these waters for Na^+, Ca^{2+}, and Mg^{2+} have been reported as 5.70, 2.64, and 1.36 mol m^{-3} for Imperial Irrigation District water with a conductivity of 140 mS m^{-1} (Kaddah and Rhoades, 1976) and 0.90, 1.27, and 0.66 mol m^{-3} with a conductivity of 46 mS m^{-1} for Twin Falls Canal Company water (Carter et al., 1973).

Regression Analysis

Regression equations from laboratory and field calibrations, and select field calibrations created with possible sources of variation (e.g. trafficked vs. nontrafficked furrows) were compared statistically using the methods outlined by Steel and Torrie (1980, p. 239–269) and Neter and Wasserman (1974, p. 160–166). These procedures tested for differences in the regression functions using Student's t test, and determined whether identified differences lay in the slope, intercept, or both.

Regression analysis was also used to attempt predicting the slope of the hand-shaken laboratory calibration, the slope of the mechanically blended laboratory calibration, or their difference. The slopes (or their difference) for each of the eight soils were regarded as the dependent variables and each of 13 soil property components (listed in Table 2) were used as independent variables. The r^2 of these 39 first order linear equations are presented in Table 2. The same procedure was repeated for 25 common nonlinear equation forms. Only five of the resulting 975 regressions produced $r^2 > 0.6$. These additional five equations appear in Table 3.

RESULTS AND DISCUSSION

Comparison of Laboratory and Field Calibrations

Laboratory calibration of settling volume in Imhoff cones to dry soil determined by the filter-paper method are presented in Fig. 1 for six of the eight soils studied. Generally, the laboratory calibrations differed among soil series, as would be expected. Regressions of all eight soils were affected by agitation method (hand shaken or mechanically blended). These two levels of agitation were selected to provide a reasonable estimate of the calibration variation range that could be expected. The magnitude of possible calibration shifts can be estimated from the slope differences between calibration lines of hand-shaken vs. mechanically blended samples (Table 2). Larger calibration shifts were expected and found for soils with higher clay contents. This result was caused by the longer settling time required for fine-clay particles. Soils with higher clay contents had more suspended clay-sized particles after mechanical blending. It is unlikely that furrow irrigation could disperse clays to the extent created in the blended samples.

Figures 2 and 3 present laboratory and field calibrations for two additional soils (Portneuf and Holtville). Field calibrations for both soils corresponded closely to the shaken laboratory calibration but were not statistically identical at $P \le 0.05$. It should be noted that no attempt was made to compensate for temperature or water quality effects in the field. Some of the extensive field data for the Portneuf soil collected during a 2-yr period appear in Fig. 2. Sources of possible calibration shift include tillage treatments, successive irrigations, trafficking of furrows, and use

Table 3. Selected nonlinear regression equations predicting the slope of manually shaken or mechanically blended laboratory calibration lines or their slope differences for the Imhoff-cone vs filtered samples in relation to selected particle size and organic-matter content combination.

Equation form	Mixing method (y)	Equation description†				
		x	A	B	C	r^2
$y = 1/(A + Bx)$	manually shaken	S	0.823	0.00523	—	0.61
$y = 1/A(x + B)^2 + C$	manually shaken	S × OM	−0.0000362	−0.000113	1.22	0.66
$y = A + Bx + C/x$	mechanically blended	S	0.691	0.00132	−1.42	0.93
$y = Ax^{B/x}$	mechanically blended	S × OM	0.859	−2.79	—	0.98
$y = A \exp(x - B)/2$	slope difference	(S + Si)OM	0.0838	121	—	0.91

† S = % sand, Si = % silt, OM = % organic matter; A, B, and C are constants.

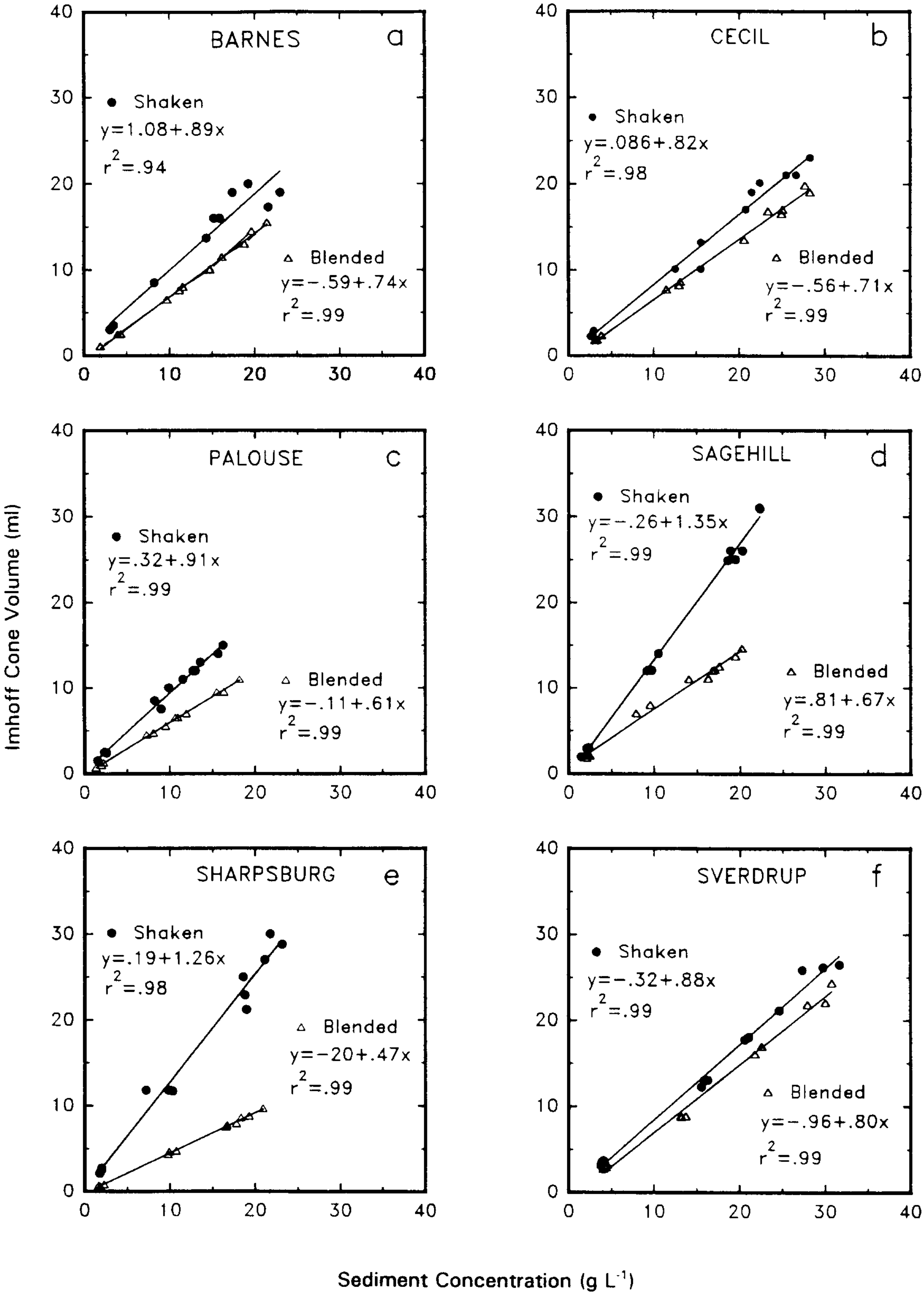

Fig. 1. Laboratory calibrations of 0.5-h Imhoff-cone settling volumes vs. total suspended sediments for six soils.

of different fields with identical soil classificaiton. Trafficked and nontrafficked furrows produced statistically dissimilar calibrations (Fig. 2b and 2c) for 1989 and 1990, which also differend statistically from laboratory calibrations.

Similarly, field data from the Holtville soil (Fig. 3) corresponded closely to the shaken laboratory calibration, but differed statistically ($P \leq 0.05$) for samples collected from the initial furrow runoff vs. subsequent surge irrigations. The field and laboratory calibrations did not correspond as well as for the Portneuf soil. The slope of the Holtville field calibration is slightly

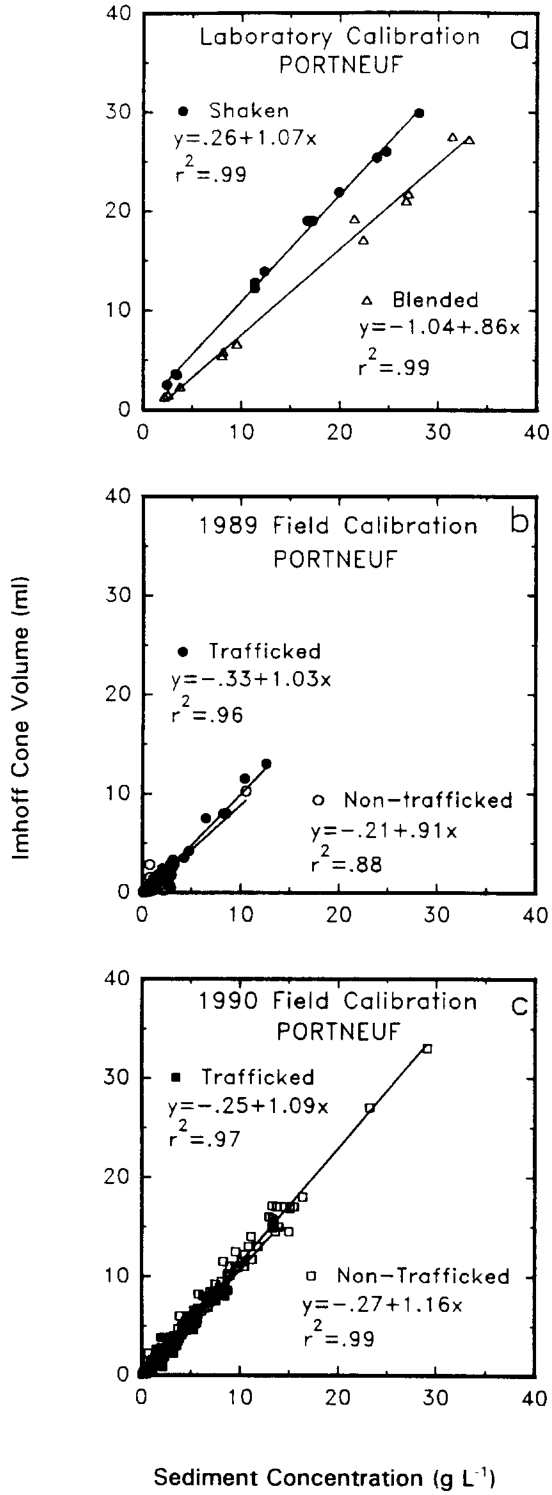

Fig. 2. Laboratory and 1989 and 1990 field calibrations of 0.5-h Imhoff-cone settling volumes vs. total suspended sediments for Portneuf soil.

higher than the laboratory calibration, and this difference was greater than for the Portneuf soil. This was probably the result of the difference in water quality at the two sites. Since Imperial Irrigation District water is typically high in salts it could affect clay flocculation and aggregate stability, increasing the Imhoff-

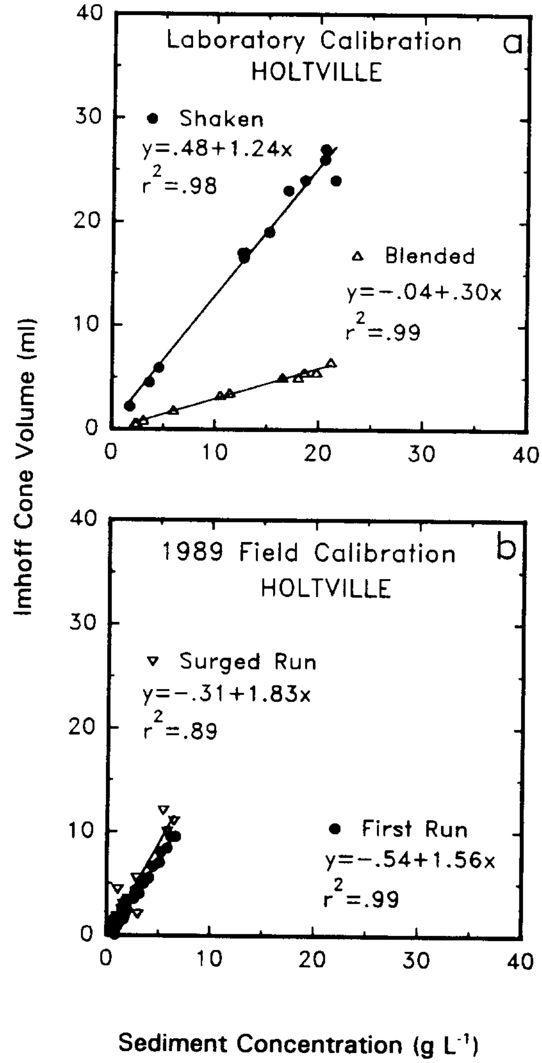

Fig. 3. Laboratory and 1989 field calibrations of 0.5-h Imhoff-cone settling volumes vs. total suspended sediments for Holtville soil.

cone settling volume, and raising the slope of the field calibration line.

Although hand-shaken laboratory calibrations and field calibrations differed statistically, examination of individual regressions reveals that this is largely the result of the low scatter (high r^2) of each regression. The errors resulting from use of a hand-shaken laboratory calibration to predict field results would be small because of the small differences in intercept and slope values between regressions across the range of interest. This is generally the case with field cultural-factor effects on regressions as well. Among the greatest discrepancies were those induced by salt effects for the Holtville soil. While these differences would warrant creation of individual calibrations for research purposes, they would not be large enough to preclude use of a laboratory hand-shaken calibration for diagnostic purposes on soils for which no field calibrations were available.

Field calibrations were most reliable for sediment concentrations above ≈ 1.0 g L^{-1}. Below this concentration, the volume of settled sediment was typically < 1 mL. The design of the Imhoff cones used in these studies prevented accurate volume estimates < 1 mL. When regression analysis was restricted to sample concentrations of < 1.0 g L^{-1}, both slopes and intercepts varied with no apparent pattern from one data set to the next, apparenty related only to observer bias. Samples in this range, however, usually constitute a small fraction of the population and represent negligible levels of erosion.

Calibration Relationships to Soil Properties

An attempt was made to predict the linear slope of the laboratory calibration lines using particle-size and organic matter components in various combinations (Tables 2 and 3). All calibrations should theoretically pass through the origin; therefore, an ability to predict the slope of the calibration would permit estimating a linear calibration equation. Table 2 presents all combinations attempted using a linear model, whereas Table 3 presents only those nonlinear models with $r^2 >$ 0.60 for 25 curve forms tested. Employing particle-size distributions to predict the slope of the settling relationship is difficult because of the inability to account for mean aggregate size of the soil sample or the sample's aggregate stability. These properties vary from soil to soil and change with time and exposure to various environmental influences (Bullock et al., 1988; Lehrsch et al., 1991). No attempt was made to rationalize the superiority of one curve type over another.

Tables 2 and 3 suggest that, where substantial precision is needed, a field calibration specific for the site should be obtained. For rapid diagnostic purposes, however, or for surveys where soil properties are only available from a data base or where the scale of application dictates less precision (e.g., with geographical information systems) calibration estimated from texture and organic matter may be adequate. However, it would be prudent to enlarge the data base beyond the eight soils used in this study to establish a better empirical predictor of slope dependency on soil properties. These data also suggest that use of a laboratory calibration using 30 s of hand shaking in distilled water to disperse the calibration samples provided a close approximation to field calibration for two soils with contrasting soil taxa, textures, mineralogies, and organic-matter contents.

Communication with other soil scientists who have begun to use this technique support its wide geographical applicability (J.W. Bauder, Montana State Univ., and R.B. Daniels, North Carolina State Univ., personal communications). Their experience has suggested that precision of low-concentration runoff is best obtained with standard Method no. 224C, and that pipetting aliquots of supernatant solutions at 30 min give a close estimate of water-suspended clay contents.

CONCLUSIONS

The relationship between volume of soil settled in 1-L Imhoff cones after 0.5-h settling time and actual sediment concentration (Weight of sediment per unit volume of suspension) was excellent for the eight soils used in this study. For the two soils observed in the field, there was good although not statistically identical agreement between calibration of sediment concentration derived in the field and 30-s hand-shaken laboratory calibration. Field calibration of settling volume vs. weight of suspended sediment was affected by furrow wheel traffic. Although statistically significant, the magnitude of the effects was small. The slope of field-calibration lines compared with a laboratory calibration using distilled water may be affected by salts in the irrigation water. Imhoff-cone settling volume of suspended sediments at 0.5-h settling time can be used to make rapid assays of suspended-sediment concentrations from irrigation runoff where concentrations typically exceed 1.0 g L^{-1}. This technique can be used to increase the intensity of field monitoring of erosion from irrigated land. It can also be helpful to scientists, coservationists, and extension personnel for making rapid diagnostic assessments of erosion severity.

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