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Use of Transparency Tubes for Rapid Assessment of Total Suspended Solids and Turbidity in Streams

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ABSTRACT

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Studies were conducted to evaluate the use of transparency tubes to predict total suspended solids concentrations (TSS) and NTU turbidity in streams. Linear regression of data collected from 29 sample stations (12 streams) in northeast Ohio revealed a highly predictive correlation for both parameters using the Ohio Sediment Stick©. Laboratory studies showed significant differences between water clarity readings among individual observers using the Ohio Sediment Stick©. The type of visual end point target used in the tube had no effect on water clarity readings. A table to predict TSS concentrations based upon water clarity was developed for the Ohio Sediment Stick©. A comparison of three tubes of differing design (e.g., Minnesota Pollution Control Agency tube, NOAA GLOBE tube, and Ohio Sediment Stick©) found no significant differences in the relationship of water clarity measurement vs. TSS concentrations or NTU turbidity among tubes. Our data indicate that predictive equations developed for the Ohio Sediment Stick© can be applied with statistical confidence to both the MPCA tube and the NOAA GLOBE tube. When appropriately used, transparency tubes can be an effective and inexpensive monitoring tool to estimate relative sediment loads to lakes from different watersheds.

Key Words: transparency tube, NTU turbidity, non-point pollution, total suspended solids, volunteer monitoring, streams, Ohio Sediment Stick©, MPCA tube, NOAA GLOBE tube.

Assessing the amount of sediment transported by flowing waters is important for effective management of lakes and their watersheds. Accurate estimation of material loads requires continuous recording of both suspended solids and flow under varying runoff conditions. While emphasis in lake studies usually is placed on the measurement of sediment load, and subsequent loss of lake volume, the concentration of total suspended solids (TSS) can itself significantly impact water quality. Reduced transparency due to soil particles can inhibit fish feeding, decrease algal productivity, detract from recreational uses, and increase the costs of treatment for potable water (Baker 1988). Sediment particles also can present a source of chemical contamination through the adsorption of heavy metals, pesticides and nutrients (Gianessi and Peskin 1981). In general, suspended solids can be considered to be a pollutant when it exceeds natural concentrations and has a detrimental effect on water quality in its biologic and aesthetic sense (Dunne and Leopold 1978).

The concept of quantifying turbidity *in vitro* began in the early 1900s with the invention of the Jackson Candle Turbidimeter (Whipple and Jackson 1900). Subsequently, standard analytical methods have been developed to quantify the concentration of TSS in water based either on direct laboratory measure of material in stream water that does not pass through a filter or an indirect estimate by measure of nephelometric turbidity units (NTU) using a nephelometer (APHA 1995). While the direct laboratory measurement of TSS and NTU turbidity is accurate, it can be costly and time consuming when multiple samples must be collected, preserved, transported to a laboratory, and analyzed. As increased emphasis is placed on sampling at the sub-watershed scale, a rapid assessment technique that allows for multiple suspended solid samples to be collected in a short time, over a wide geographic area, would be useful for a wide variety of soil and water resource management applications.

The use of field analytical tools to estimate water clarity has a long history in limnology. The Secchi disk has been used for more than 100 years to measure lake water transparency (Effler 1988), and to estimate nutrient enrichment or trophic state as measured by algal chlorophyll pigments (Carlson 1977). The Secchi disk, however, has limited use in most streams. Poor access makes it difficult to view the disk where a bridge does not cross the stream, and fast current and the limited depths of many stream channels makes use of the Secchi disk impractical in most flowing water situations.

In 1991, Noel Morgan, working in Australia, expanded the lentic Secchi disk concept to flowing waters (White 1994). Morgan developed a simple device for use by farmers to estimate the water clarity of streams. Christened the "Morgan Bottle Turbidimeter," the device consisted of a plastic soft-drink bottle with a symbol painted on the bottom, calibrated in NTUs. Morgan believed that the involvement of farmers in the monitoring of stream turbidity, both during and after rain runoff, would help to identify areas of soil erosion and where best management practices would be needed (White 1994). Subsequent changes to the Morgan Bottle resulted in the creation of a "turbidity tube," a 60 cm (2 feet) long clear plastic cylinder into which stream water is poured until a symbol on the bottom of the cylinder is no longer visible (White 1994). This tube, calibrated in NTU units, currently is used by the Australia Department of Conservation in their "Waterwatch" citizen monitoring program [see http://www.waterwatch.org.au].

Based in part on the Australia initiative, the use of transparency tubes was recommended by the U.S. EPA (1997) in their citizen stream monitoring methods manual [information available at http://www.epa.gov/volunteer/]. In 1997, the Minnesota Pollution Control Agency (MPCA) began to use a "transparency tube" for their Citizen Stream Monitoring Program (MPCA 1999, MPCA 2000) [see information at http://www.pca.state.mn.us/water/csmp.html]. Transparency tube data were calibrated against NTU turbidity (r^2 = 0.86) and TSS (r^2 = 0.75) to allow for statistical prediction of these chemical parameters (MPCA 2000). The MPCA transparency tube can be used to target violations of the Minnesota water quality criteria for turbidity of 25 NTU units (MPCA 1999), making the MPCA tube a useful monitoring tool for citizens to document stream water pollution. In 1998, the National Oceanic and Atmospheric Administration (NOAA), National Geophysical Data Center in Boulder, Colorado, began a worldwide student volunteer water quality monitoring network called the GLOBE Program [information available at http://www.globe.gov]. To our knowledge, this GLOBE transparency tube has not previously been calibrated against TSS or NTU turbidity.

A modified Australian type turbidity tube, the Ohio Sediment Stick©, was developed in 1997 by the Lake Soil and Water Conservation District in Ohio [see information at http://www.lakecountyohio.org/soil/other%20neat%20stuff.htm]. This modified tube was used by staff at the Ohio Environmental Protection Agency to determine if a statistical association could be developed between stream water transparency as measured by the Ohio Sediment Stick©, and the concentration of TSS and NTU turbidity as determined by standard laboratory methods. Simultaneous measurements of stream water clarity using the Ohio Sediment Stick©, the MPCA transparency tube, and the NOAA GLOBE tube were conducted to determine whether or not there are differences in predicting TSS concentrations or NTU turbidity based on the type of tube used.

Methods

Tube Construction

The Ohio Sediment Stick© (Fig. 1) is constructed of clear acrylic tubing which has an inner diameter of 2.54 cm, and an outer diameter of 2.83 cm (CADCO acrylic tubing, Cadillac Plastic and Chemical Co., Cleveland, OH). The tubing was cut to a total length of 91.44 cm (36 inches), and labeled with a 91 cm x 2 cm clear enamel decal that is printed with 36 one-inch gradations for making water clarity measurements (Lake Marking Products, Solon, Ohio). White bottom caps [SC 1.187-16 (1"IL) OTH caps, Stock Cap Corp., St. Louis, MO] are labeled with a 1 cm circular black mark (or "dot") with a permanent marking pen and placed securely on the bottom of the Ohio Sediment Stick©. The permanent "dot" is used as the target for determining the water clarity end point. Because the Ohio Sediment Stick© is calibrated in inches, we reference both metric and English units in our discussion of data for this tube.

Transparency tubes used by the Minnesota Pollution Control Agency ("MPCA tube") and the NOAA GLOBE monitoring program ("GLOBE tube") were provided courtesy of the manufacturer. Both tubes are 4.5 cm in diameter, but differ in materials of construction and total length (Fig. 1). The 60 cm MPCA tube is constructed of clear PVC, while the 120 cm or 100 cm GLOBE tube is constructed of clear polycarbonate plastic. The MPCA tube is equipped

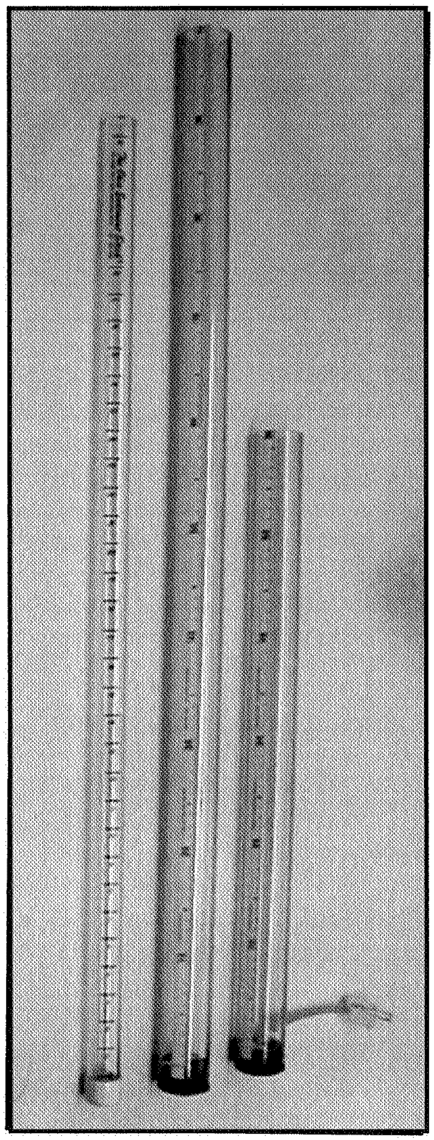


Figure 1.–Transparency tubes evaluated: the Ohio Sediment Stick© (left); the NOAA GLOBE tube (center); and the Minnesota Pollution Control Agency tube (right).

with a valve to allow for gradual release of water. Both the MPCA and NOAA tubes use an alternating black and white quadrant pattern as the target for determining end point, and both used taped-on scales marked in centimeters for the measurement of water height.

Field Studies

A field study to calibrate the Ohio Sediment Stick© with laboratory TSS and turbidity was conducted between July 8, 1998 and July 8, 1999. Water samples were collected from streams monitored by the Ohio EPA as part of the National Ambient Water Quality Monitoring Program, or in conjunction with routine water quality surveys conducted by the agency. Data were collected from 29 sampling sites on 12 streams. Twenty of the sampling locations were located within the Erie Ontario Lake Plain ecoregion; nine were located within the Western Allegheny Plateau ecoregion. Two Ohio EPA staff members were responsible for collecting the samples. Water samples for the analysis of TSS and NTU turbidity were collected concurrently to the measurement of Ohio Sediment Stick© clarity to determine the relationship between clarity and laboratory analysis of the stream water.

The field study to compare readings from the Ohio Sediment Stick©, the MPCA tube and the GLOBE tube was conducted between January 11 and August 8, 2000. Water samples were collected concurrently with the measurement of water clarity using each of the three tubes, and were submitted to the laboratory for the analysis of TSS and NTU turbidity. Water samples and field measurements were collected from eight different National Ambient Water Quality Monitoring Program stations by four field staff.

Stream water samples for water clarity readings were collected either directly into the transparency tube by holding it in the flowing water with the open end pointing upstream, or by collection into a clean container that had been rinsed with stream water. Water in the container was stirred thoroughly prior to pouring into the transparency tube to prevent settling of suspended materials. Water clarity readings were taken by aligning the transparency tube perpendicular to the ground and within the shadow of the observer. The transparency tube either was filled or emptied "until the end point target (dot or quadrant pattern) just became visible to the eye" from a vantage point approximately 2.5 cm from the top of the tube. No sunglasses were worn, although the use of corrective lenses was acceptable. The water clarity end point was recorded as the height of the water column measured to the nearest one half inch for the Ohio Sediment Stick©, and to the nearest centimeter for the MPCA and GLOBE tubes. In cases where the target was clearly visible when the transparency tube was full, the water clarity reading was recorded as greater than the maximum tube length. The process was repeated twice for each sample, and the average height was used as the final reported reading.

Stream samples collected for laboratory analysis were either collected directly into a clean polyethylene sample container that had been pre-rinsed with stream water or were transferred immediately from a clean, pre-rinsed sampling container that had been used to collect a water sample from the stream. Water samples were immediately cooled to 4° C, and were transferred to the Ohio EPA Division of Environmental Services Laboratory for analysis. All sampling and analytical methods followed the Ohio EPA quality assurance manual (Ohio EPA 1995). Total suspended solids concentration was measured using EPA Method 160.2 (APHA Method 2130) (U.S. EPA 1993, APHA 1995), and was reported in $mg \cdot L^{-1}$. Turbidity was measured using EPA Method 180.1 (APHA Method 2450 B) (U.S. EPA 1993, APHA 1995), and was reported in NTUs.

Data collected from the field studies were analyzed using linear regression techniques from Sokal and Rohlf (1969) and Mack (1967). The data were linearized following Weisberg (1985) by using an inverse square transformation of the transparency tube readings followed by a logarithmic transformation. A 95% predictive limits belt was constructed using critical values of the Student's *t*-distribution about various points on the linear regression.

Volunteer Experiments

Volunteer studies were conducted under controlled experimental conditions to determine whether significant differences exist between individual observers when using different Ohio Sediment Sticks©, or when the target placed on the bottom cap was changed from a 1 cm dot to an alternating black and white quadrant Secchi type pattern. In the first experiment (volunteer experiment no. 1), highly turbid stream water was collected from a tributary to the Cuyahoga River in northeast Ohio. From this sample, five different dilutions were made by mixing the stream water with de-ionized water to create a range of water clarity samples for observation. Three randomly chosen Ohio Sediment Sticks© were used in the experiment and labeled correspondingly as Ohio Sediment Sticks© A, B and C. Random assignments of water dilutions and Ohio Sediment Sticks© were made for thirty volunteers so that each volunteer conducted two measurements for three different dilutions, using a different Ohio Sediment Stick© for each dilution assigned. Results were recorded to the nearest 0.25 inch. A total of 180 measurements were made consisting of 60 measurements for each Ohio Sediment Stick© and 36 measurements for each dilution. Aliquots of each dilution were collected at the end of each day for laboratory analysis for TSS and NTU turbidity.

The second volunteer study (volunteer experiment no. 2) was designed to determine if there was any advantage to alternative configurations of the target used to determine the water clarity endpoint for the Ohio Sediment Stick©. In this experiment, three dilutions of stream water were formulated using the methodology described above. One of the Ohio Sediment Sticks© was altered to change the water clarity target at the bottom to an alternating black and white quadrant, similar to the design of a Secchi disk. Seven volunteers conducted duplicate measures of each dilution with both types of Ohio Sediment Stick© and reported results to the nearest 0.25 inch. Each volunteer also was asked to assess which target they felt allowed them to best discern the water clarity endpoint. Statistical analysis of data collected from both volunteer studies was accomplished by performing a three-way nested analysis of variance (ANOVA) with replication (Sokal and Rohlf 1969).

Results

Field Studies

Water clarity readings for the Ohio Sediment Stick© during the calibration study ranged from 3.2 cm (1.25 inches) to greater than 91.4 cm (36 inches). A total of 97 measurements of Ohio Sediment Stick© clarity were taken in conjunction with the collection of water for analysis of TSS. Laboratory turbidity measurements were taken on 57 of the water samples. Total suspended solids concentrations ranged from less than the analytical detection limit (5 $mg \cdot L^{-1}$) to 286 $mg \cdot L^{-1}$, while laboratory turbidity measurements ranged from 1 to 244 NTU.

Ohio Sediment Stick© readings that were greater than the length of the Ohio Sediment Stick© were excluded from the analysis for purposes of evaluating the regression correlations of Ohio Sediment Stick© readings with laboratory measurements. Measurements taken in conjunction with water samples where the TSS concentration was determined to be less than the analytical detection limit were also excluded. A total of 22 measurements were excluded from the regression analysis of Ohio Sediment Stick© clarity vs. TSS.

Linear regression analysis for transformed data of Ohio Sediment Stick© clarity vs. TSS, and the 95th percent predictive limits interval estimate for the line of best fit, were calculated (Fig. 2). The regression analysis yields the following relationship between these parameters:

$$\log(TSS) = 3.38 + 0.659 \cdot \log(SSC^{-2}) \quad r^2 = 0.896, n = 75 \quad (1)$$

where: TSS = total suspended solids concentration ($mg \cdot L^{-1}$), and SSC = Ohio Sediment Stick© water clarity (cm).

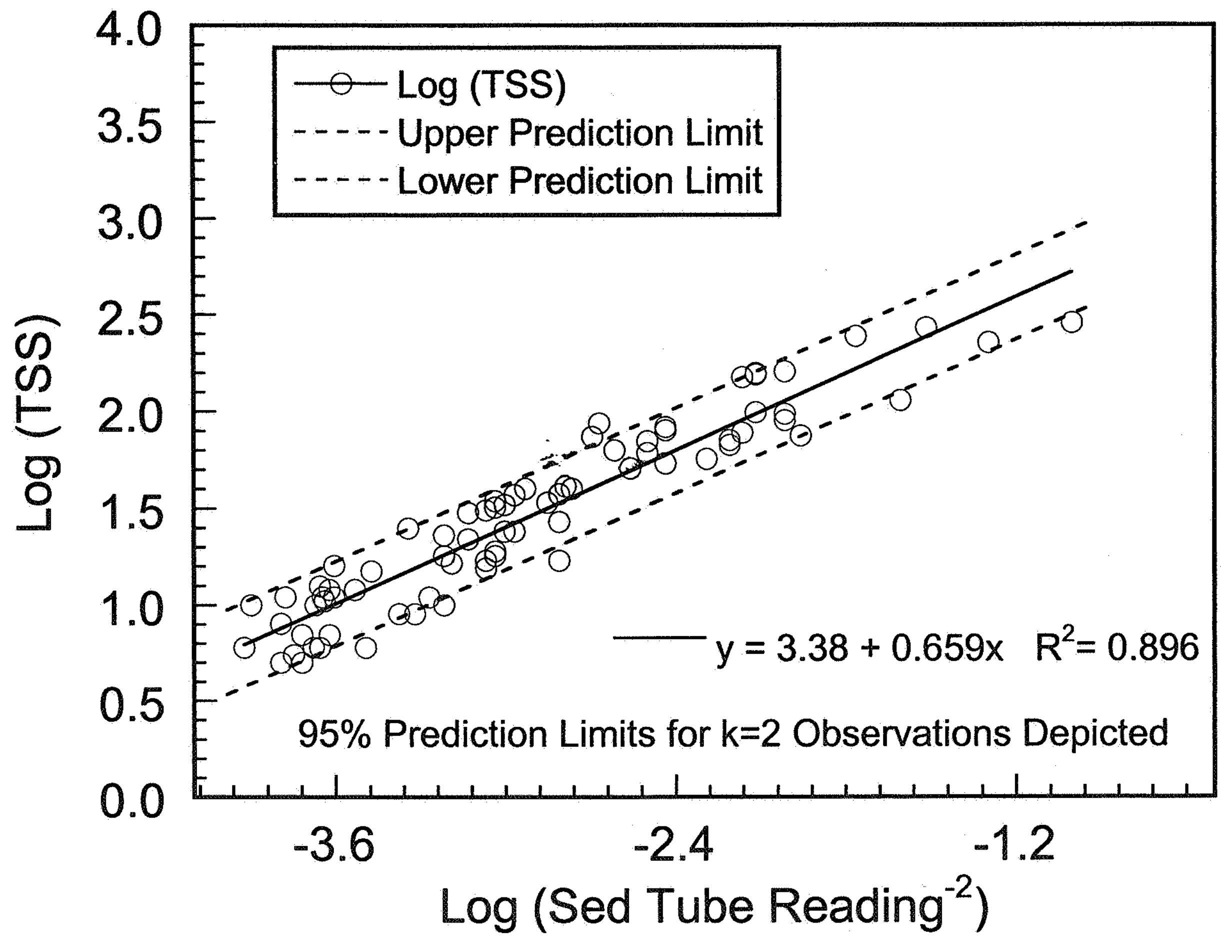


Figure 2.–Linear regression and 95th percent prediction intervals (k = 2 observations) for transformed field study data. Sediment tube readings in centimeters, TSS values in mg · L^{-1}.

To visualize the relationship between Ohio Sediment Stick© clarity and TSS concentrations, the curve of best fit and the 95th percent predictive limits interval estimates derived from the field experiment are presented as a semi-log plot (Fig. 3).

The strong coefficient of determination in equation (1) indicates a high degree of predictability of TSS concentrations from Ohio Sediment Stick© readings collected in northeast Ohio streams. A predictive table based upon equation 1 and the 95th percent predictive limit estimate for k = 2 observations is presented in Table 1. Use of Table 1 enables TSS concentrations to be estimated in the field in the absence of laboratory analysis.

Linear regression analysis of the relationship between Ohio Sediment Stick© clarity and laboratory turbidity measurements yielded a similarly strong correlation according to the following equation:

$$\log(\text{Turbidity}) = 3.25 + 0.658 \cdot \log(\text{SSC}^{-2})\quad r^2 = 0.896,\quad n = 51 \qquad (2)$$

where: Turbidity = laboratory turbidity (NTU), and SSC = Ohio Sediment Stick© water clarity (cm). Based upon these data, a similar relationship exists to

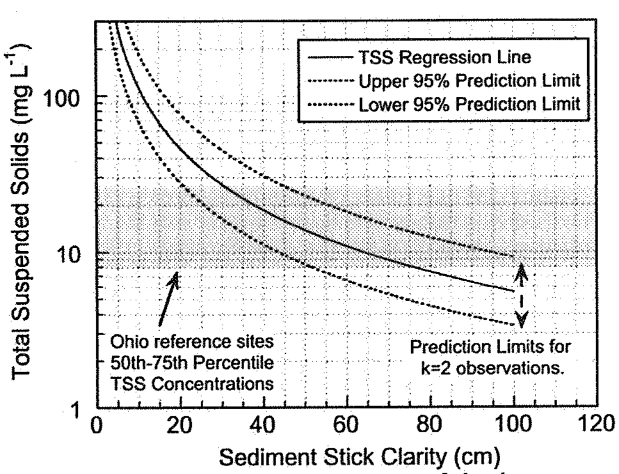


Figure 3.–Prediction limits for the Ohio Sediment Stick© water clarity readings and TSS concentrations for Northeast Ohio streams.

predict turbidity values in NTUs as that shown for predicting concentrations of TSS.

The results of the transparency tube comparison study are summarized in Table 2. Linear regression analyses for transparency tube readings vs. TSS concentration and vs. turbidity measured in NTUs resulted in strong coefficients of determination for all three tubes tested in the study (Fig. 4). Comparisons of the resulting regression statistics found no significant differences between either the slopes of the predicted regression lines ($p>0.50$ for both TSS and turbidity), or the intercepts ($p>0.10$ for TSS, $p>0.50$ for turbidity). The null hypothesis that the three tubes share a common regression line cannot be rejected ($p>0.25$ for TSS, $p>0.50$ for turbidity). These data indicate that the Ohio Sediment Stick©, the MPCA tubes and the GLOBE tube generate equivalent results when used to predict TSS concentrations and NTU turbidity in flowing waters.

Laboratory Studies

The results of volunteer experiment no. 1 to test for differences between individual observers and

Table 1.–Field conversion table for predicting total suspended solids (TSS) concentrations (mg·L^{-1}) from Ohio Sediment Stick© water clarity readings in centimeters (inches). Upper and lower estimates reflect 95% prediction limits for a sample mean based upon observations (also applicable for MPCA and GLOBE tubes).

Ohio Sediment Stick© Water Clarity in cm (inches)	Predicted TSS (mg·L^{-1})	Upper TSS Prediction Limit (mg·L^{-1})	Lower TSS Prediction Limit (mg·L^{-1})	Ohio Sediment Stick© Water Clarity in cm (inches)	Predicted TSS (mg·L^{-1})	Upper TSS Prediction Limit (mg·L^{-1})	Lower TSS Prediction Limit (mg·L^{-1})
1 (0.4)[1]	2400	4003	1439	34 (13.4)	23	38	14
2 (0.8)[1]	962	1601	578	35 (13.8)	22	37	13
3 (1.2)[1]	564	937	339	36 (14.2)	21	35	13
4 (1.6)	386	641	232	37 (14.6)	21	34	12
5 (2.0)	287	477	173	38 (15.0)	20	33	12
6 (2.4)	226	375	136	39 (15.4)	19	32	12
7 (2.8)	184	306	111	40 (15.8)	19	31	11
8 (3.1)	155	256	93	42 (16.5)	17	29	10
9 (3.5)	132	220	80	44 (17.3)	16	27	10
10 (3.9)	115	191	69	46 (18.1)	15	26	9
11 (4.3)	102	168	61	48 (18.9)	15	24	9
12 (4.7)	91	150	55	50 (19.7)	14	23	8
13 (5.1)	81	135	49	52 (20.5)	13	22	8
14 (5.5)	74	123	45	54 (21.3)	12	21	8
15 (5.9)	67	112	41	56 (22.0)	12	20	7
16 (6.3)	62	103	37	58 (22.8)	11	19	7
17 (6.7)	57	95	35	60 (23.6)	11	18	7
18 (7.1)	53	88	32	62 (24.4)	10	17	6
19 (7.5)	49	82	30	64 (25.2)	10	17	6
20 (7.9)	46	77	28	66 (26.0)	10	16	6
21 (8.3)	43	72	26	68 (26.8)	9	15	6
22 (8.7)	41	67	25	70 (27.6)	9	15	5
23 (9.1)	38	64	23	72 (28.3)	9	14	5
24 (9.4)	36	60	22	74 (29.1)	8	14	5
25 (9.8)	34	57	21	76 (29.9)	8	13	5
26 (10.2)	33	54	20	78 (30.7)	8	13	5
27 (10.6)	31	52	19	80 (31.5)	7	12	5
28 (11.0)	30	49	18	82 (32.3)	7	12	4
29 (11.4)	28	47	17	84 (33.1)	7	12	4
30 (11.8)	27	45	16	86 (33.9)	7	11	4
31 (12.2)	26	43	16	88 (34.6)	7	11	4
32 (12.6)	25	41	15	90 (35.4)	6	11	4
33 (13.0)	24	40	14	>92 (36)	<5		

[1]Values extrapolated from regression coefficients; outside range of monitored data.

Table 2.–Summary of results from the tube comparison study.

	Ohio Sediment Stick©	MPCA Tube	GLOBE Tube	TSS ($mg \cdot L^{-1}$)	Turbidity (NTU)
Tube Length (cm)	91	60	100		
Number of measurements greater than tube length	6	8	5		
Number of analyses less than the analytical detection limit				6	1
Number of detectable measurements	32	27	33	32	27
Minimum measurement	10 cm	13 cm	13 cm	7 $mg \cdot L^{-1}$	3 NTU
Maximum measurement	72 cm	59 cm	95 cm	128 $mg \cdot L^{-1}$	98 NTU

different Ohio Sediment Sticks© under controlled conditions of water clarity are presented in Fig. 5. The range and average Ohio Sediment Stick© water clarity measurements, as well as the results of laboratory analyses for TSS and NTU turbidity, are presented in Table 3. Results of the three-way nested ANOVA with replication for volunteer experiment no. 1 (Table 4) show that the Ohio Sediment Sticks© can be used to differentiate waters of varying concentrations of TSS and NTU turbidity at a high degree of statistical confidence ($p<0.001$). No significant differences were detected between the three Ohio Sediment Sticks© used, indicating that there is consistency in water clarity readings among individual tubes ($p>0.05$). However, a significant statistical difference ($p<0.001$) for Ohio Sediment Stick© clarity was observed among volunteers evaluating the same water sample. These data indicate that variance among individuals conducting surveys of water clarity must be accounted for. The magnitude of this observer error is predictable and decreases as stream water turbidity increases (Fig. 5).

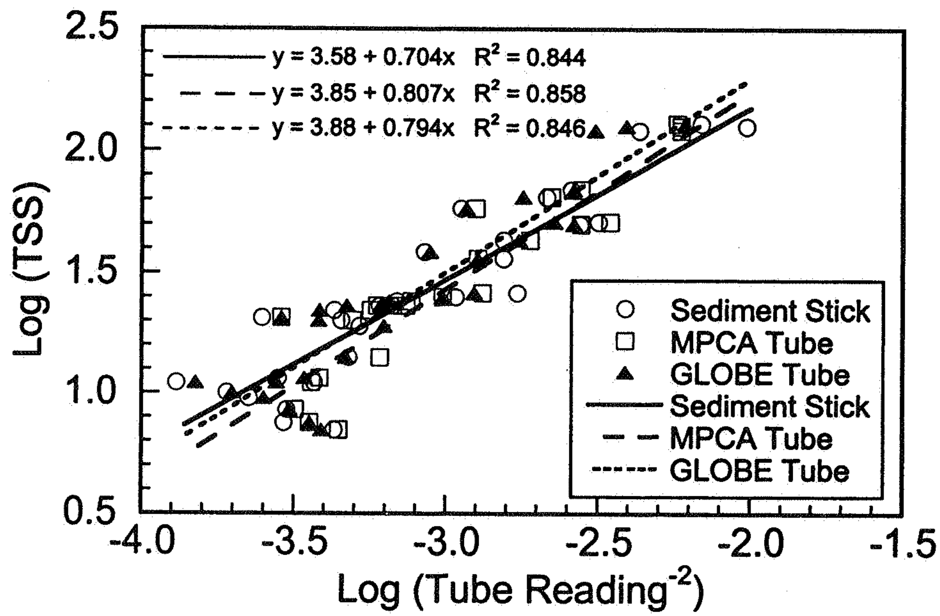
Results from the three-way ANOVA with replication for volunteer experiment no. 2 (designed to test for differences between "dot" and "quadrant" visual targets) indicated no statistically significant difference for water clarity readings taken with Ohio Sediment Sticks© using two different end point targets ($p>0.5$). The choice of target used for end point determination does not influence the determination of Ohio Sediment Stick© water clarity under varying TSS concentrations.

Written responses of the volunteers participating in volunteer experiment no. 2 indicated no clear preference regarding the type of end point target used to determine the water clarity value. Forty-four percent of the responses indicated an opinion that the "dot" target provided for an easier determination of end point, 28 percent indicated a preference for the "quadrant" target, and 28 percent indicated no discernible difference. Responses of the individual volunteers varied dependent upon the clarity of the water observed, but no clear preference was detectable.

Discussion

The data presented in this investigation (Figs. 2 and 4, Table 2), and studies conducted by the MPCA (MPCA 2000), indicate that transparency tubes can be used to estimate both TSS and NTU turbidity with a high degree of statistical confidence over a wide range of concentrations in flowing water habitats. The results from our volunteer experiments indicate that the highest degree of predictive confidence occurs when multiple samples are collected by a single individual. However, transparency tube data collected by different individuals can be used to accurately distinguish stream waters with differing clarity (Fig. 5).

Transparency tubes can be an important addition to a water quality monitoring program as long as the data limitations and uncertainty are recognized. Tube readings can be used to quantify rapid changes in suspended solids over the ascending and descending curves of a stream hydrograph during and after precipitation events, estimate sediment loads from different land uses during the same storm event, monitor the downstream movement of a first flush event, and to quantify temporal changes in sediment concentrations and loadings upstream and downstream of potential sources. A high degree of correlation of TSS concentrations or NTU turbidity measurements with concentrations of nutrients such as total phosphorus has been demonstrated in some stream studies (Grayson et al. 1996). Where such a relationship exists, water clarity measurements using turbidity tubes may be valuable in constructing watershed nutrient budgets.



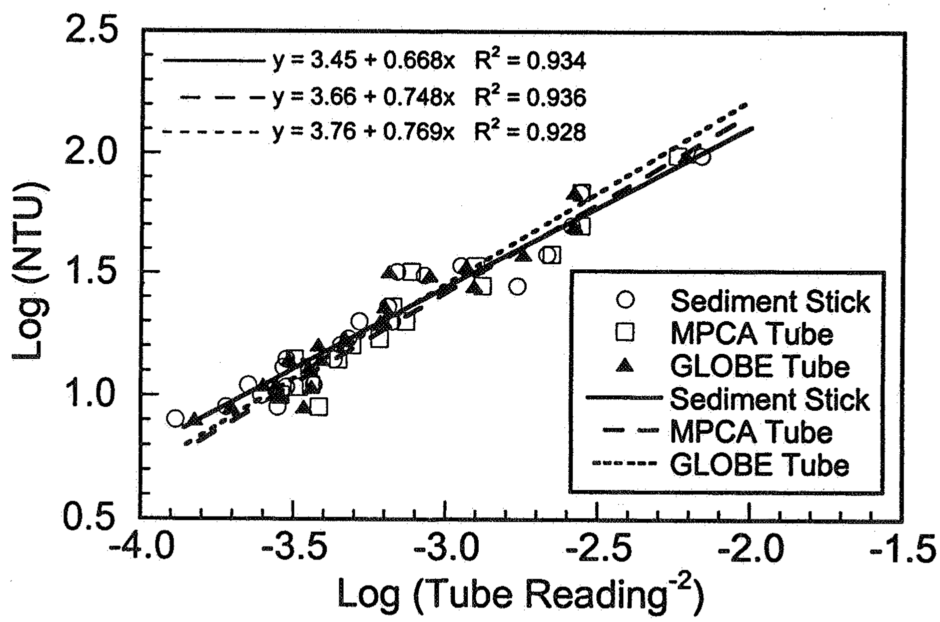


Figure 4.–Results of regression analysis for the comparison study using the Ohio Sediment Stick©, the NOAA GLOBE tube, and the Minnesota Pollution Control Agency tube for TSS ($mg \cdot L^{-1}$) (upper) and NTU turbidity (lower). Sediment tube readings in centimeters.

In Minnesota, use of a 60 cm long PVC tube gives predictive estimation of potential violations of the state water quality standard based upon NTU turbidity (MPCA 1999, MPCA 2000). However, based on the data in MPCA (1999), the restricted length of the tube does not appear to allow for accurate estimation of TSS at concentrations below 20 mg $\cdot L^{-1}$, while our results indicate that 10 mg $\cdot L^{-1}$ TSS is the lower limit

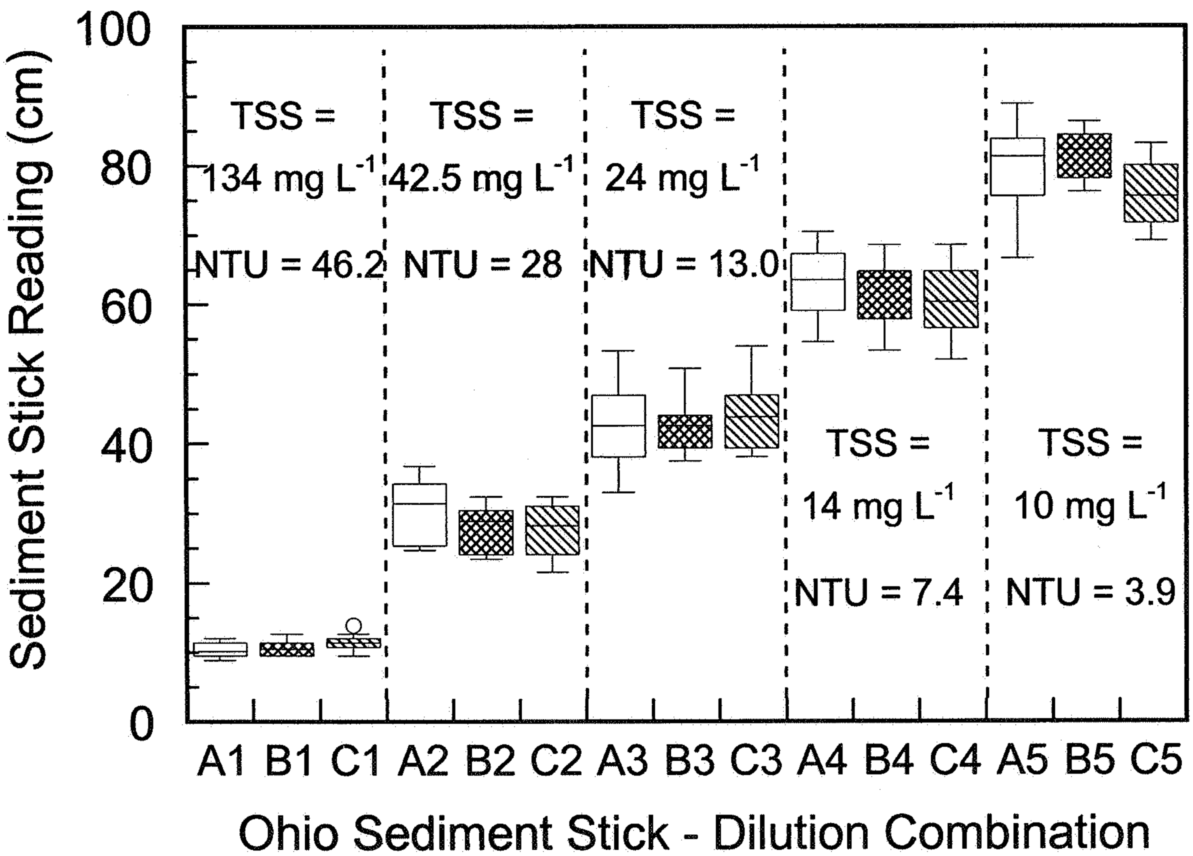


Figure 5.–Results of volunteer experiment no. 1.

of predictability using the MCPA tube for Ohio streams. The use of longer transparency tubes such the Ohio Sediment Stick©, and the NOAA GLOBE tube, allows for the determination of TSS concentrations and NTU turbidity to a detection limit of 5.0 mg·L^{-1}. However, our experience with the 1 m long GLOBE tube is that the longer length can make it unwieldy in the field. For this reason, we believe that the Ohio Sediment Stick© is preferable for use when accurate measurements are necessary at low TSS concentrations. We found the use of the MCPA tube to be preferable for measurement when the stream water had moderate to high turbidity (i.e., TSS concentrations ≥20 mg·L^{-1}) because of the larger end point target and the ease of releasing water from the bottom of the tube to determine the final end point. We suggest that the Ohio Sediment Stick© could be improved by the addition of a bottom release valve such as that used on the MCPA tube.

The cost savings to a monitoring program by using transparency tubes, as compared to more accurate laboratory measurement of TSS and NTU turbidity, can be substantial when multiple samples are required. In addition to laboratory costs, much higher costs are associated with personnel time in collecting the sample, material costs in sample collection equipment and containers, and sample shipping and handling. Sample costs would range into the hundreds of

Table 3.–Summary of the results for volunteer experiment no. 1(pooled data of readings from three Ohio Sediment Sticks©).

	Dilution	1	2	3	4	5
Ohio Sediment	Maximim	14	36	54	71	89
Stick©	Minimum	9	22	33	52	67
Water Clarity (cm)	Average	11	29	43	62	79
Total Suspended Solids (mg·L^{-1})		134	43	24	14	10
Turbidity (NTU)		46	28	13	7	4

Table 4.–ANOVA summary table for volunteer experiment no. 1.

Source of Variation	Degrees of Freedom	SS	MS	F_s	Result
Among Dilutions	4	104127.4	26036.85	762.15	Significant at p<0.001
Among Tubes Within Dilutions	10	341.6	34.16	1.08	Not Significant (p>0.25)
Among Volunteers Within Tubes	90	2851.1	31.68	8.92	Significant at p<0.001
Error	75	266.3	3.55		
Total	179	107586.4			

dollars if it was necessary to submit samples to a laboratory to monitor multiple streams in a watershed for TSS during a single precipitation runoff event.

We suggest that use of the upper and lower confidence intervals of predicted TSS as presented in Table 1 for the Ohio Sediment Stick© would be the most appropriate way to address the statistical problem of uncertainty between transparency tube clarity and TSS concentration. This statistical uncertainty includes a variety of components such as error in collection of the stream water sample, natural variability in soil characteristics across watersheds, and error between individuals in reaching the end point of tube water clarity. One can use uncertainty to advantage if its nature has been quantified. As shown in Fig. 3, the association between TSS and Ohio Sediment Stick© water clarity is a non-linear function, and the predictive power of the regression equation becomes increasingly more accurate as stream turbidity decreases. The greater uncertainty in tube readings at higher levels of stream turbidity (Table 1) is mediated by the fact that the individual error of estimating TSS significantly decreases at this end of the regression curve (Fig. 3). The practical difference in the error of estimating TSS as being 69 $mg \cdot L^{-1}$ or 191 $mg \cdot L^{-1}$ (95% predictive interval at a 10 cm tube reading, Table 1) becomes inconsequential when viewed in the context of reference background concentrations, or for recommending watershed and land use best management practices. When using the Ohio Sediment Stick© to compare many different streams from the same region to determine which stream has the highest relative concentration of TSS, we suggest use of the "predicted TSS" statistic from Table 1, because sampling error should be standardized among the sample stations.

In Minnesota, the MPCA has found that there can be significant differences between the relationship of stream turbidity and transparency tube readings from streams in different watershed regions (MPCA 2000). Concerns over possible differences in soil characteristics among major watersheds or ecoregions of the United States (79 ecoregions recognized by the USDA, Natural Resources Conservation Service) can be addressed by calibrating local soil conditions to the regression coefficients presented in equation (1). This can be accomplished by selective sub-sampling at equal intervals of TSS concentrations over the range of values used to develop equation (1). The results of our study suggest that any of the three turbidity tubes tested (e.g., Ohio Sediment Stick©, MPCA tube, NOAA GLOBE tube) can be used to estimate TSS using the statistical data summarized in Table 1.

We caution against using transparency tube data to estimate TSS when the purpose of the sampling is for potential litigation. Another obvious imitation of using transparency tubes to estimate TSS is the fact that some waters are bog-stained (tea colored), however such waters are easily recognized from their lack of suspended matter. Care must also be used that water obviously dominated by planktonic algae not be compared against the data presented in Table 1. The data in Table 1 represent stream samples where water clarity was predominately determined by silt and clay turbidity, not algae.

Conclusions

The results of our field tests and volunteer experiments indicate that the use of transparency tubes has broad application for low cost stream monitoring programs. Transparency tubes provide a rapid and statistically accurate field estimation of TSS concentration or NTU turbidity in stream water. No significant differences in the correlation of water clarity readings with either TSS concentrations or NTU turbidity were noted between the Ohio Sediment Stick©, the MPCA tube, and the GLOBE tube, three devices commonly in use in volunteer stream monitoring programs. These similarities permit the effective communication of data between researchers using these different transparency tubes. Although some limitations to the use and accuracy of transparency tubes to predict TSS and NTU turbidity exist, they can be taken into account. The benefits of reduced cost and the ability to collect more data in a shorter period of time, in comparison to standard laboratory techniques, commend the use of transparency tubes as an effective tool in stream data acquisition.

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