TURBIDITY SENSORS TRACK SEDIMENT CONCENTRATIONS IN RUNOFF FROM AGRICULTURAL FIELDS

Seth M. Dabney, Research Agronomist, USDA-ARS, Oxford, MS, sdabney@ars.usda.gov; Martin A. Locke, Research Leader, USDA-ARS, MS, mlocke@msa-oxford.ars.usda.gov; R. Wade Steinriede, Biologist, USDA-ARS, Oxford, MS, rsteinriede@ars.usda.gov

Abstract: Optical backscatter (OBS) turbidity sensors offer the opportunity to obtain a continuous record of soil loss if turbidity is well correlated with sediment concentration. The relationship between turbidity and sediment concentration depends on several factors, including: particle size, particle shape, and particle color. As watershed size is reduced to the scale of individual fields or plots, variability in particle composition is reduced and the relationship between turbidity and concentration may become stable. We undertook studies to determine this relationship for several fields using OBS-3 turbidity sensors. We compared concentration - turbidity relationships for both suspensions of dried soil samples and sequential natural rainfall runoff samples from three ~15-ha fields. We obtained strong correlations between turbidity and concentration, but the relationships differed between natural runoff and resuspended samples. Overall, turbidity explained 95% of the variability in sediment concentration observed in natural runoff samples from one of the fields that was used for calibration. When the resulting regression relationship was applied to two adjacent but independent fields, accuracy of prediction was similar. Prediction accuracy was only marginally improved by consideration of additional parameters including discharge, rate of change of discharge, and time within runoff event, indicating little hysteretic behavior. Peak turbidity usually preceded both peak flow rate and the time of collection of the first sequential sample. We conclude that calibrated optical backscatter turbidity sensors placed in edge-of-field grade control pipes have good potential for continuously monitoring soil loss and improving field-scale soil loss estimates with an expected accuracy estimated to be about 0.5 t ha^{-1} y^{-1}. When combined with measured concentrations, turbidity data they may provide an indication of the particle size distribution of sediment in transport.

INTRODUCTION

Turbidity has been shown to be strongly correlated with suspended sediment concentration, but calibration relationships often vary between locations, between events at a location, or even within an individual event hydrograph (Lewis, 1995). The main factors that influence the relationship between turbidity and suspended sediment concentration are: particle size, shape, spectral reflectivity, and bulk refractive index (Downing, 2005). Most testing of turbidity-suspended sediment relationships has been conducted in streams, estuaries, and oceans; much less experience exists relating turbidity to edge-of-field sediment concentration.

For conservation compliance, average annual erosion rates must be held below a “tolerable” level. To measure the effect of management on erosion, cumulative discharge is usually combined with sediment concentration determined on flow-weighted composite samples. Such samples provide no information of erosion dynamics.

We hypothesized that turbidity vs. suspended sediment calibration would become more stable as the size of drainage areas was reduced to individual agricultural fields because soils and contributing areas would become less variable. The objective of this study was to evaluate the utility of turbidity for improving assessment of erosion loss from agricultural fields.

METHODS

Submersible optical backscatter turbidity sensors (OBS-3[1], D & A Instrument Company Port Townsend, WA) calibrated using formazine so that 4000 NTU output 2 volts were used in this study. These sensors employ an 875 nm infrared LED light source and a detector made up of four photodiodes that integrate infrared light scattered between 140 and 160 degrees.

The sensors were deployed within 0.56-m diameter grade control pipes made of smooth steel (Fig. 1) draining three 15 to 17 ha agricultural fields (Fig. 2) at the Delta Demonstration Conservation Center <http://www.dcdcfarm.org/>. The predominant soil in the fields was Sharkey [Very-fine, smectitic, thermic Chromic Epiaquerts] clay, silty clay or very fine sandy loam. The fields were all precision graded during 2001 to between 0.1 and 0.15% slope (Fig. 2). Sampling was conducted between July 2002 and March 2004. Cotton (*Gossypium hirsutum* L.) was grown in field 7 in 2002 and 2003, in field 5 during 2002, and in field 3 during 2003. Corn (*Zea mays* L.) was grown in field 3 during 2002 and in field 5 during 2003. Both

Figure 1 Photographs illustrating instrument deployment in pipe and flow conditions with irrigation tailwater.

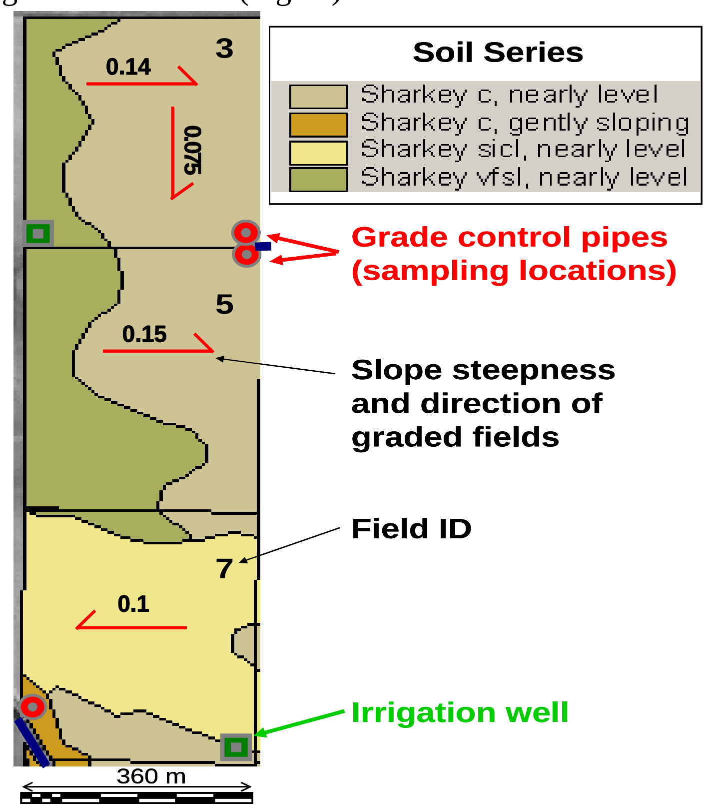


Figure 2 Soils, field grades, and locations of irrigation wells and sampling points of the three adjacent fields studied.

[1] Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

cotton and corn were planted on hipped rows spaced 0.97-m apart and running with the slope. Both crops were grown without tillage (no-till) each year after the initial row construction following grading. Runoff water was accumulated in a tail ditch graded toward the pipe outlet at the lower end of each field.

In addition to the turbidity meter, a Doppler flow meter (ISCO 4150), a 24-bottle sequential sampler (ISCO 3700), and a datalogger (Campbell Scientific 510) were deployed at each sampling site. All sensors were attached to a removable array that included a 7.5-cm high weir that increased depth during low flows (Fig. 1). The pump sampler intake tube was located just upslope of the weir and had five intake points distributed at depths between 1 and 6 cm. A sluice at the base of the weir provided a sediment outlet. Pipes were set at ~1% grade. The turbidity sensor was deployed at an angle that permitted the sensor head to be located close to the pipe wall while minimizing IR beam reflection off the pipe. This arrangement was designed to maximize the ability of the instrumentation to monitor low flow conditions. A fin was designed to help shed plant debris that might be wrap around the turbidity sensor.

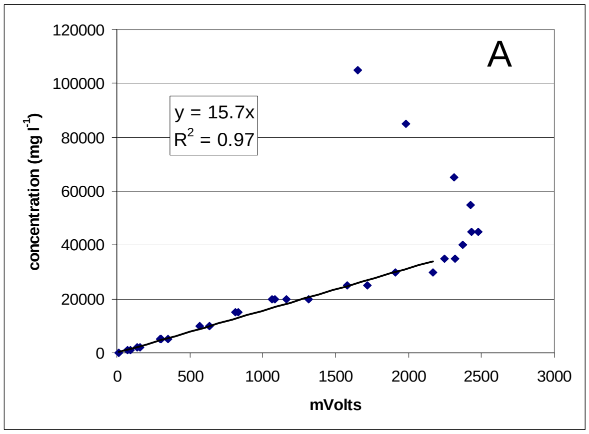
Instruments were programmed to log depth, flow, and turbidity information at 1-minute intervals during flow periods, and to pump a 900-ml sample whenever 340 m^3 of flow had taken place. Sediment concentration was determined by flocculating the samples with 10 ml of 0.05 M $Al_2(SO_4)_3$, followed by settling, decanting, drying, and weighing.

Data were analyzed using a mixed linear model to determine relationships to predict sediment concentration based on turbidity and flow parameters at the same minute that samples were pumped. In this analysis, events were separated using the criterion that no discharge was observed for 5 hours. Event within a field was considered a random effect, and samples within events were considered repeated measure sub-samples with an exponential covariance structure based on sampling time after the start of the event. Flow parameters evaluated included discharge, rate of change of discharge, flow depth, flow velocity, time into the event and time relative to the first, largest, and last peak of the flow event. Rate of change of discharge was determined on a centered 2-hour moving average of the one-minute measurements in order to minimize the effect of short-term noise on discharge gradients. Turbidity measurements were collected as the average of 120 individual readings within each minute. Data from each field were analyzed separately in order to optimize prediction sediment concentration based on turbidity and flow parameters for each field. These results were then compared with the ability to predict concentration in fields 3 and 5 based only on the relationships derived from field 7. The Mixed procedure (SAS, 1996) was used to perform calculations.

In a preliminary study, soil collected from a nearby Sharkey silty clay soil was returned to the laboratory, dried, and crushed to pass a 2-mm sieve. Weighed amounts of this soil were added to 3 l of water in a stirred bucket at ~5-min intervals, and responses of two OBS-3 sensors were recorded. The final slurry was separated into particle (aggregate) size classes with a settling tube (Dabney et al., 2001), quantified with Imhoff cones, and the sensitivity of the OBS-3 to these separated size fractions was determined. Also, soil samples collected from fields 7, 5, and 3 were analyzed for texture using a pipet method to estimate clay after removing organic matter with hydrogen peroxide, dispersion by overnight shaking with Na-hexametaphosphate, and sand separation using a sieve (Gee and Or, 2002).

RESULTS

The sensitivity of the OBS-3 to increasing concentrations of Sharkey silty clay loam soil added to a mechanically stirred bucket is shown in Fig. 3A. A linear relationship existed up to ~30,000 mg l^{-1}, while at concentrations above ~60,000 mg l^{-1} response decreased. A 2.5 V voltage clamp may have limited the response of the instrument at intermediate sediment concentrations.



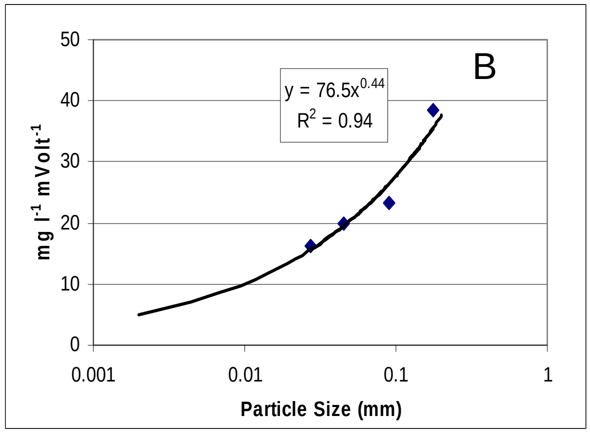


Figure 3 Turbidity measured in the laboratory when dried, ground soil samples of Sharkey sicl soil was sequentially added to a stirred bucket showed a linear response to concentrations up to 30,000 ppm (A). Instrument sensitivity to aggregate size class (plotted at geometric mean size) separated by settling showed a decreasing sensitivity of the calibration equation to increasing particle size (B).

Assessment of sensitivity to aggregated particle size fractions separated based on fall velocity demonstrated a 2.5 fold decrease in sensitivity between particle size classes of 0.028 and 0.18 mm geometric mean diameter (Fig. 3B). It is well known that finer particles produce more turbidity per unit mass than do coarser particles (Conner and DeVisser, 1992). The sensitivity to particle size seen here is similar to that reported by Sutherland et al. (2000). The sensitivity observed in the bulk stirred soil sample of 15.7 mg l^{-1} per mVolt suggests an effective sediment size of about 0.03 mm (Fig. 3B) for this laboratory test.

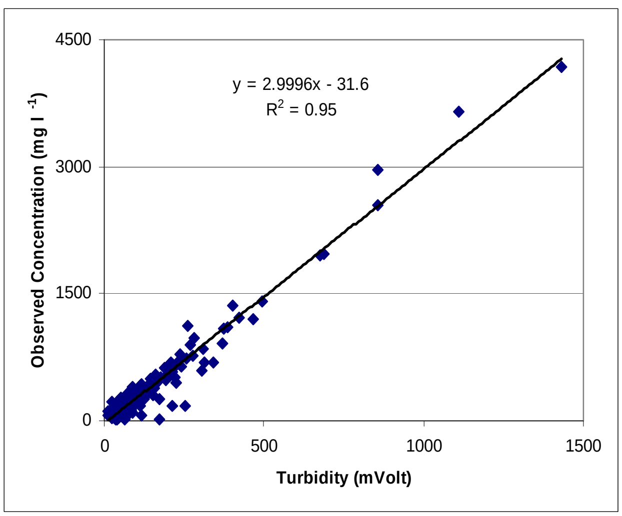


Figure 4 Regression of concentration vs OBS-3 turbidity for all samples taken in Field 7 with synchronous turbidity data collection.

Sensitivity of samples collected from Field 7 (Fig. 4), was five times greater than observed in the laboratory (discussed above), suggesting the field-generated sediment had a finer particle size distribution than that derived from dried, sieved soil samples. The regression equation (Fig. 4) estimated from 272 observations explained approximately 95% of the observed variation in sequential samples taken during the same minute that the turbidity readings were averaged. The standard error of the intercept estimate was 15.8 with 23 degrees of freedom and that of the turbidity coefficient was 0.0452 with 247 degrees of freedom. When the rate of change of discharge at the time of sampling was added to the regression model, it was found to be a statistically significant effect, but its influence was so small as to be of no practical value. Therefore no significant or consistent hysteretic effects were observed in the relationship between turbidity and suspended sediment concentration in runoff leaving this 15-ha cotton field.

In order to test the utility of the regression equation developed in Field 7, it was applied to the 232 simultaneously measured turbidity and concentration samples available from Field 3 (90 samples) and Field 5 (142 samples). Figure 5 presents the observed and predicted concentrations for all three fields.

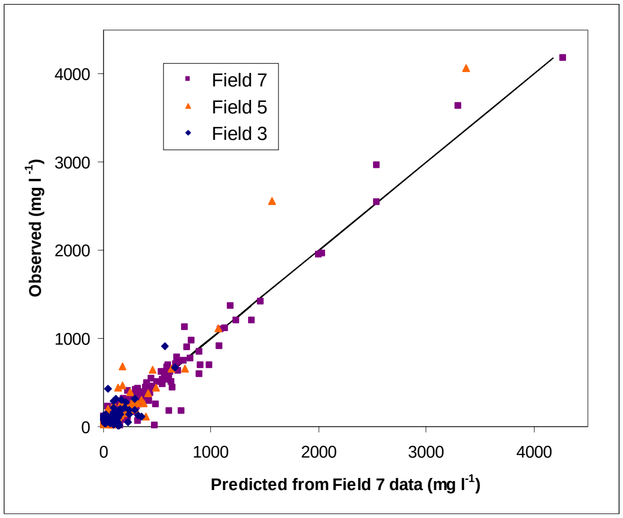


Figure 5 Observed concentrations from all fields plotted against the concentrations predicted from the regression equation derived from Field 7 data alone.

Examination of the difference between predicted and observed concentrations showed that prediction precision of sediment concentration in rainfall runoff was similar in all the fields (Table 1). In the calibrated Field 7, the mean of the differences between observed and predicted values was close to zero (-3 mg l^{-1}) with a standard deviation of 95 mg l^{-1}. For Field 3, the results were similar (mean difference 5 mg l^{-1} with standard deviation of 97 mg l^{-1}), although the range of observed concentrations was smaller. In Field 5 the mean difference of 35 mg l^{-1} with a standard deviation of 135 mg l^{-1} was significantly different from zero. The two large positive residuals for Field 5 (Fig. 5, 6) would be better predicted if a calibration had been optimized separately for that field because large values exert a large effect on regression parameters. However, as discussed below, some of these differences may be related to uncertain synchrony of sampling and turbidity measurement during periods of rapidly changing concentration.

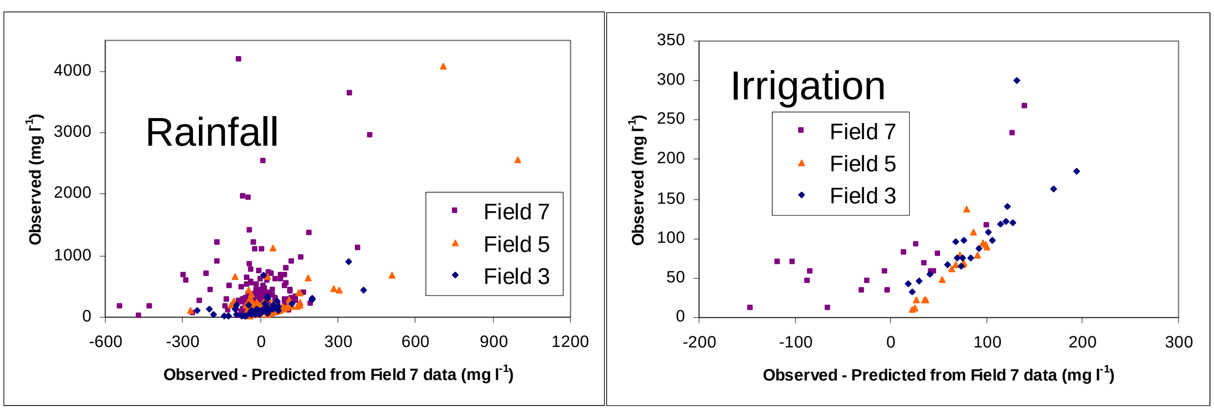


Figure 6 Differences between observed and predicted sediment concentrations plotted against observed concentration for samples derived from rainfall runoff or irrigation tailwater. Differences of rainfall samples are distributed around zero with 2 large positive outliers for Field 5. In contrast, differences for irrigation tailwater from fields 3 and 5 were uniformly positive, indicating that irrigation sediment concentrations, although low, were consistently underpredicted by the Field 7 turbidity calibration equation.

Table 1 Number of samples and mean and standard deviation of the difference between observed and predicted sediment.

Field	Source	n	Mean (mg l^{-1})	Std. Dev. (mg l^{-1})
3	Rainfall	69	5	97
	Irrigation	21	90	46
5	Rainfall	125	35	135
	Irrigation	17	65	27
7 (calibrated)	Rainfall	253	-3	95
	Irrigation	19	-4	82

Samples derived from irrigation tailwater (excess furrow irrigation water) in fields 3 and 5 had consistent higher suspended sediment concentrations than predicted from the Field 7 turbidity calibration (Table 1, Fig. 6). As discussed later, this may have been associated with coarser sediment derived from concentrated flow erosion (in the absence of raindrop impact).

Figure 7 illustrates the application of the calibration equation to produce a continuous predicted concentration trace that tracked observed concentrations in discrete sediment samples. Figure 7A shows some of the Field 7 data from the calibration dataset, while 7B shows results applied to an independent dataset from Field 5. Both hydrographs displayed in Fig. 7 illustrate the typically observed tendency for turbidity peaks to precede flow peaks and for turbidity and concentration to be highest at the beginning of runoff events and to increase briefly as new maximum event discharge levels were approached for the first time.

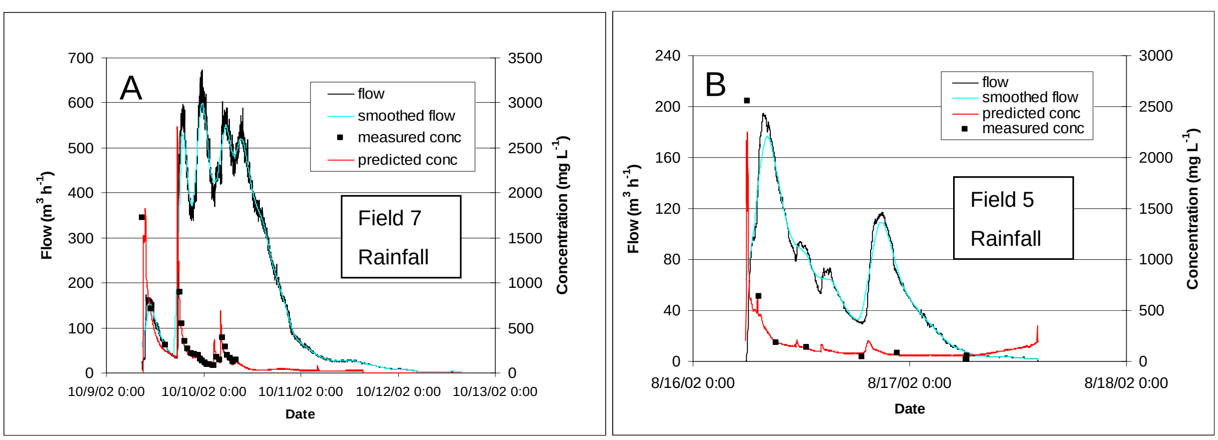


Figure 7 Selected hydrographs and sedigraphs derived from measured samples and from OBS-3 sensors using the calibration equation derived from Field 7 samples (Fig. 4). Both the raw flow and the smoothed (2-hr centered moving average) flow that was used to determine rate of change of flow are displayed.

All of the sampler bottles were used before the end of the large 3-day flow event of Fig. 7A, but the turbidity data provided information that the unsampled portion of the event had even lower sediment concentrations than that in the last sample bottle. Although the agreement between observed and turbidity-predicted concentrations was generally good for the event recorded in Fig. 7B, the difference between observed and predicted concentrations for the first sample of the event represents the largest deviation in the Field 5 record (Fig. 6). In fact, both DCDC5 differences exceeding 600 mg l^{-1} (Fig. 6) were associated with rapidly changing concentrations near the start of runoff events. The increase in predicted concentration at the end of Fig 7B, probably represents an artifact associated with sediment deposition around the turbidity sensor mounted near the bottom of the pipe (Fig. 1). Such artifacts have little effect on estimated event sediment yield but illustrate the need for routine sensor maintenance between events.

DISCUSSION

The systematic tendency for the turbidity to under predict suspended sediment concentration of irrigation events in fields 3 and 5 may be related to two factors. In these fields, unlike in Field 7, the grade control pipes were set at elevations that were from 15 to 30 cm lower that those of the adjacent fields. In contrast, the invert of the grade control pipe in Field 7 was about 5 cm higher than the adjacent field. The low grade control elevations in fields 3 and 5 allowed headcut or ephemeral gully erosion at the lower end of the tail ditch during flows that did not create flow depths in the pipes sufficiently deep to submerge the lower ends of the fields. Such erosion was evident in these fields and was progressive over time. During large storms that filled the pipes to capacity, these headcuts became submerged and were presumably less active. Because surface irrigation tail water did not reach submergence depths, headcut erosion could have occurred during the irrigation events, and may have added coarse aggregated sediment to flows that were otherwise relatively clear because irrigation runoff events also lacked the detachment of fine sediment that can be caused by raindrop impact. Thus, while the runoff leaving the fields due to irrigation had low suspended sediment concentrations, the sediment that was in transport probably had a coarser particle size distribution than was found in the rainfall runoff events that dominated the calibration relationship. Visual observations confirmed the presence of large soil aggregates and pieces of particulate organic matter rolling along the bed within relatively clear irrigation water runoff (Fig. 1).

The relatively high mean difference between observed and predicted sediment concentration (Table 1) for irrigation tailwater and the tendency for these differences to increase with increasing measured concentration (Fig. 6) suggests: (1) that the pump sampler was able to sample the coarse sediment moving through the pipe, and (2) that because of the low range of concentrations observed and the small response of turbidity to those concentrations, the turbidity sensor technique would not be well suited to monitoring soil loss in similar slow flows that transport sediment predominantly as bedload.

CONCLUSIONS

OBS turbidity sensors have proven useful for monitoring sediment yield from three agricultural fields. The fields studied were (selected to be) similar in many respects: 15 to 17 ha in size, 0.1 to 0.15 slope gradient, silty clay texture, and no-till management. Under these similar conditions, the calibration of one turbidity meter in one of the fields successfully predicted the suspended sediment concentration in runoff from the other two fields using different turbidity meters. Errors of prediction of suspended sediment concentration within the calibration and independent datasets were similar, with standard deviations of approximately 100 mg l^{-1} for individual rainfall runoff event samples. An error of ±100 mg l^{-1} applied to annual runoff volume of 500 mm per year implies an error of about ±0.5 t ha^{-1} in estimated annual soil loss, a level of uncertainty that is acceptable for assessing conservation practice effectiveness.

No within-event hysteretic or seasonal trends were observed in the relationship between sediment concentration and turbidity for rainstorm runoff. Turbidity and sediment concentration were found to be largest at the start of runoff events, with concentration peaks generally preceding flow peaks. Turbidity was not a good predictor of sediment concentration in irrigation tailwater runoff, but sediment concentrations were generally low during these events.

When watersheds are reduced to the scale of individual agricultural fields, and where soil and management are uniform, many of the factors that affect the OBS response to suspended sediment are minimized. Under these conditions, we suggest that calibrated OBS sensors have good potential for improving field scale sediment yield estimates. Further, the continuous records they provide give an indication of erosion process dynamics. Finally, we suggest that when turbidity measurements are combined with measured concentrations, deviations of observed and predicted concentrations provide an indication of the particle size distribution of the sediment in transport. In agricultural runoff at the field scale, much sediment is transported in the form of silt- and sand-sized aggregates (Meyer et al, 1992). The size distribution of these aggregates, as with that of the sediment “flocs” that develop in oceans and estuaries, alters sediment transport and turbidity relationships compared to those of completely dispersed primary particles. Knowledge of sediment particle size distribution and composition is important for predicting the efficiency of best management practices such as filter strips and detention basins that depend on sediment settling for improving water quality. Combining turbidity and concentration measurements at the field scale can provide an indication of the sediment size distribution if the other factors that affect the turbidity response to suspended sediment (particle mineralogy, shape, reflectivity, and bulk refractive index) vary within narrow limits. In this study, turbidity and concentration data suggested that sediment eroded during furrow irrigation was coarser and created less turbidity than sediment eroded by rain storms. Particle size analysis of eroded sediments would be needed to unequivocally prove this conclusion.

REFERENCES

Conner, C.S. and De Visser, A.M. (1992). “A laboratory investigation of particle size effects on an optical backscatterance sensor,” Marine Geology 108, pp 151-159.

Dabney, S.M., Cullum, R.F., and Smith, S. jr. (2001). “Automated sediment size discriminator,” Proc. of the Seventh Interagency Sedimentation Conference I, Reno, NV, pp 152-159.

Downing, J. (2005). “Turbidity monitoring,” *In* Environmental Instrumentation and Analysis Handbook. John Wiley & Sons, New York. pp 511-546.

Gee, G.W., and Or, D. (2002). “Particle-size analysis,” *In* J.H. Dane and Topp, G.C. (eds.) Methods of Soil Analysis. Part 4. Physical Methods. Soil Science Society of America Book Series No. 5, Soil Science Society of America, Madison, WI, pp 255-293.

Lewis, J. (1996). “Turbidity-controlled suspended sediment sampling for runoff-event load estimation.” Water Resources Research 32(7), pp 2299-2310.

Meyer, L.D., Line, D.E., and Harmon, W.C. (1992). “Size characteristics of sediment from agricultural soils,” J. Soil and Water Cons. 47(1), pp 107-111.

SAS. (1996). SAS/STAT Software: Changes and Enhancements Through Release 6.11. SAS Inst. Inc., Cary, NC.

Sutherland T.F., Lane, P.M., Amos, C.L., and Downing, J. (2000). “Calibration of optical backscatter sensors for suspended sediment of varying darkness levels.” Marine Geology 162, pp 587-597.