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**SOIL EROSION RESEARCH
FOR THE 21ST CENTURY**

Proceedings of the International Symposium

**3-5 January, 2001
Honolulu, Hawaii, USA**

**Edited By
James C. Ascough II
Dennis C. Flanagan**

**Symposium Sponsored and Published By
American Society of Agricultural Engineers
2950 Niles Rd., St. Joseph, Michigan, 49085-9659 USA**

A Dielectric Method of Sediment Concentration Measurement in Runoff Waters

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Abstract

Methods are being evaluated with the goal of constructing, calibrating, and characterizing a sediment measurement system appropriate for the flow conditions at the USDA-ARS Walnut Gulch Experimental Watershed. Data were obtained by testing a 55 cm, three-prong, embedded time domain reflectometry probe that is designed for installation in the base or side of a flume. Using a model and the empirical function describing pure water, the sensor's temperature dependence was accounted for. The instrumentation had sufficient resolution to discriminate concentration differences of 3.5 g/L on a single measurement. This sensitivity is adequate for depth integrated concentrations in monsoon flows (ranging from 4.63 to 127 g/L in a small watershed in 1999) and bed load concentrations, but will be marginal for suspended load concentrations (ranging from 0.43 to 7.8 g/L) where signal averaging will be required. Air entry is a potential pitfall, particularly in highly turbulent or near surface situations.

Keywords. Soil erosion, Sediment, Time Domain Reflectometry (TDR).

Introduction

Techniques for measuring sediment concentrations and transport have been developed and reported for at least a century. Traditional methods involve extracting a sample from the flow path and measuring sediment concentration by oven drying the sample. Variations in traditional methods are associated with the sampling technique used and these include a wide variety of the slot samplers, array and mast samplers, trap samplers, and pump samplers (Hudson, 1993). More modern automated methods that show some promise for sediment concentration measurements in certain environments and concentration ranges include capacitance solids flow sensors (Yan and Reed, 1999), turbidity meters (Wass and Leeks, 1999), acoustical methods (Shen and Lemmin, 1997; Shi et al., 1997), and optical backscatter techniques (Black and Rosenberg, 1994). However, it is not clear that any of these automated methods would be useful for the high concentrations, large particle sizes, and violent flow conditions that prevail in large-scale monsoon flows from watersheds such as the Walnut Gulch Experimental Watershed in semi-arid southeastern Arizona. This USDA-ARS facility has a long history of developing approaches to assessing sediment concentrations, transport, and yield (e.g. Lane and Nichols, 1997; Renard et al., 1993; Lane et al., 1992; Renard and Stone, 1982; Renard and Laursen, 1975; Libby, 1968). Methods currently in use for measuring sediment concentration on small watersheds (3.7-4.5 ha) at the facility include a traversing slot sampler and a depth integrated pump sampler. The measured sediment yield from the traversing slot total load sampler was up to three times higher than pump sampler measured suspended sediment yield (Simanton et al., 1993).

Starr et al. (2000) reported on the measurement of soil particle concentrations in suspension using a dielectric method. The difference in dielectric constant of water (~80) and that of soil sediment particles (~4) is such that, when the two are combined in suspension, the dielectric constant declines as the sediment concentration increases. By measuring the square root of the apparent dielectric constant (Topp et al., 1980) that is the refractive index (n) assuming negligible electromagnetic dispersion, a simple linear equation for sediment concentration calculation can be derived (ignoring bound water effects) using a linear mixing model:

$$C = \rho_s(n - n_w)/(n_s - n_w) \quad (1)$$

where C is concentration (g/L), ρ_s is the mass density of sediment solids (g/L), n is the measured refractive index in runoff waters, n_w is the refractive index of water at a give temperature, and n_s is the refractive index of solids. The n_s can be set equal to 2, ρ_s set equal to 2.65 (10)³ g/L, and n_w calculated given the measured temperature using the empirical equation (Weast, 1986):

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$$n_s = [78.54\{1 - 4.58(10)^{-3}(T-25) + 1.19(10)^{-3}(T-25)^2 - 2.8(10)^{-4}(T-25)^3\}]^{1/2} \quad (2)$$

where T is temperature ($^{\circ}\text{C}$). The purpose of paper is to report on design and initial testing of a probe for use with time domain reflectometry (TDR) to measure sediment concentrations *in-situ* in runoff waters.

Materials and Methods

The TDR probe (see Persson and Berndtsson, 1998 for a similar probe used for surface soil water content measurement) has three stainless steel rods embedded in Delrin plastic. The 55 cm long probe is designed for installation in the base or side of a flume (Figure 1) and is flush with the base to provide *in-situ* measurements while avoiding flow disturbances, cavitations, and crushing impact from rocks. A Tektronix 1502B cable tester, controlled by a laptop computer, was coupled to the probe via coaxial cable. The probe was calibrated to read n by recording TDR effective length readings in air and water at different temperatures where n was known and then performing a linear regression. This procedure eliminates the effects of the Delrin plastic so that n of the suspension could be determined and concentration calculated from Eq (1) and Eq. (2).

A calibration chamber was constructed for mixing and measuring different sediment concentrations (Figure 2). Pulverized silica powder (250 micron mesh) and water were mixed to known concentrations (ranging from 16 to 123 g/L) for comparing the sensor readout with a known standard (Starr et al., 2000) that simulates soil sediment. A rectangular box was placed over the sensor and filled with gravel, soil, and water in known size ranges (obtained by sieving bed material from a channel) and known concentrations to determine sensor response as a function of particle size. Repeated measurements at constant concentrations were used to estimate the instruments resolution limit in terms of the minimum change in concentration that can be reliably detected. Water depth was varied in the rectangular box to determine the minimum flow depth necessary for accurate measurements and to get some idea of probe sensitivity as a function of distance from the probe face. Artificial flows are being tested for *in-situ* validation of the sensor calibration in a dynamic flow environment.



Figure 1. Probe installed under simulated flow.



Figure 2. Calibration chamber and instrumentation.

Initial Results

Initial testing indicates that temperature compensation will be necessary when concentrations are low or high accuracy is required. The temperature dependence could be accounted for by using Eq. (2) describing the temperature dependence of pure water. The instrument had sufficient resolution to discriminate concentration differences of 3.5 g/L on a single concentration reading and this should improve with signal averaging. This sensitivity is adequate for depth integrated concentrations in monsoon flows (ranging from 4.63 to 127 g/L in 1999 as measured by a traversing slot sampler) and bed load concentrations, but will be marginal for suspended load concentrations (ranging from 0.43 to 7.8 g/L in a small watershed in 1999 as measured with a pump sampler). Static tests where depth of water over the probe was varied indicated that the probe must be a minimum of 2.5 cm below the water surface and this minimum depth increases if the surface is rough. A nominal 2.5 cm dynamic simulated flow (Fig. 1) was inadequate because the sensor responded to air that came into the sensor's zone of influence with the surface roughness.

The linear regression performed to calibrate for absolute n measurement was done using air ($n=1$) and water ($n=8.56-9.35$) at a range of temperatures ($T = 1.7-40^{\circ}\text{C}$). The regression analysis of 14 data points showed a

root mean square error (RMSE) of 0.090 and coefficient of determination (r^2) of 0.998 (Fig. 3). Sensor concentration readings for silica powder mixed in the calibration chamber and bed material of various size ranges were in good agreement (Fig. 4) with oven dry scale measured concentrations. The bed material concentrations (Fig. 4) were quite high because these bed material measurements were static tests of a completely covered probe. A limited dataset of cross-section integrated concentrations reported in previous work on a large flume range from about 4 to 100 g/L (Renard and Laursen, 1975). The probe is currently situated to collect concentration data at the base and center of a large flume where concentrations are expected to be at a maximum.

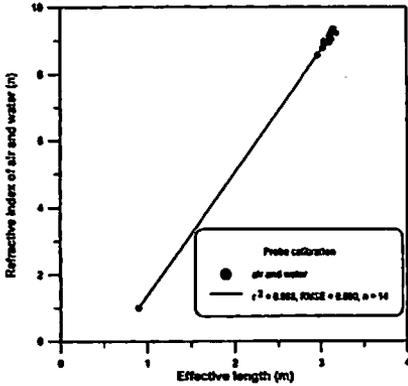


Figure 3. Probe calibration in air and water at various temperatures.

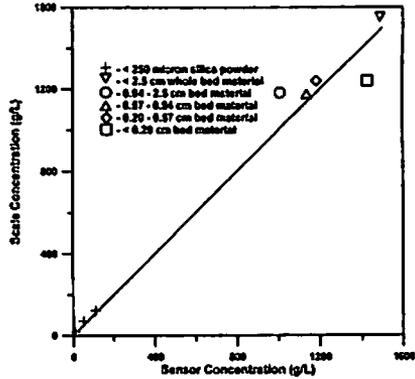


Figure 4. Comparison of sensor and scale concentrations for various particle sizes.

Summary

Initial testing of a dielectric sensor for sediment concentration measurement in runoff waters indicated good potential of the method for bed material concentrations and applications where the concentrations are high. The design allows for *in-situ* measurements without flow disturbance. Good agreement between measured and known concentrations over a wide particle size range in static tests indicates that this is a promising method that warrants further study.

Future Directions

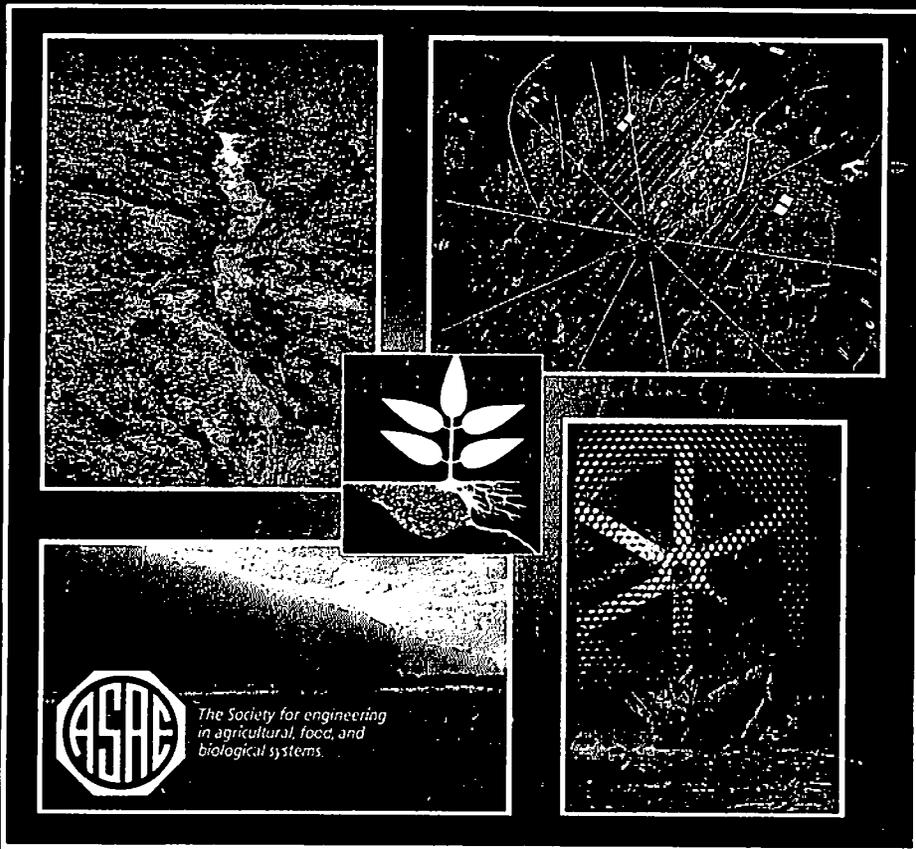
The probe is currently installed at the base and center of a large flume and data collection during monsoon flows is underway during the year 2000 monsoon season. Results from these studies along with an expanded discussion of methodology will be presented in a later report. Great progress has been made in the past two decades toward automating and customizing time domain reflectometry systems. In its current configuration the sediment sensor is expected to provide a measure of basal concentration extending at most 2.5 cm into the flow. It would be advantageous to obtain depth-integrated measures and profiles of concentration for calculation of sediment transport and yield dynamics. Probe and experimental design work with the goal of making depth-integrated and concentration profile measurements are planned for the future. Dynamic testing of customized probe designs in both simulated and actual flow environments with the goal of improving the characterization and validation of the sensor's performance is also planned.

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