ABSTRACT. Sediment concentration measurement in high-concentration runoff waters is highly problematic. A novel device was developed for high-concentration measurements. This device was then used to measure sediment concentrations during monsoon runoff events at the USDA–ARS Walnut Gulch experimental watershed in southeast Arizona as an example application. Data were obtained using a 55 cm, three-prong, embedded time domain reflectometry probe and sediments in a range of size classes from the site under laboratory conditions. In the laboratory, the sensor’s concentration output was calculated using a model and the empirical function describing pure water. Without sediment-specific calibration, laboratory validation indicated agreement with known concentrations within about 0.02 kg L$^{-1}$ for sediment and water mixtures and within 0.2 kg L$^{-1}$ when the probe was completely buried in 0 to 2.5 cm channel bed material. In the field application, the probe was installed in the base and center of a flume. Basal (0 to 2 cm depth) sediment concentrations were monitored during three flows with peak discharges of 5, 70, and 130 m$^3$ s$^{-1}$, representing small, intermediate, and large events. For the large and intermediate events, basal sediment concentrations rose from 0.4 to 1.2 kg L$^{-1}$ to a plateau of 1.5 to 1.9 kg L$^{-1}$ after the flow peak. The plateau extended through much of the tail of the hydrograph before falling back to 0.4 to 1.2 kg L$^{-1}$. The small event had a similar progression but lower overall concentrations of 0.2 to 0.8 kg L$^{-1}$. These observations are consistent with a period of high sediment transport and channel erosion in the tail of monsoon runoff hydrographs. The dielectric method provides in-situ measurements in high-concentration environments where traditional methods fail.

Keywords. Channel erosion, Dielectric, Monsoon, Rangeland, Runoff, Sediment, Soil erosion, Time domain reflectometry.

Traditional methods for measuring sediment concentrations involve extracting a sample from the flow and then oven drying the sample. The sampling techniques vary widely and include slot samplers, array and mast samplers, trap samplers, and pump samplers (Hudson, 1993). Automated methods that show some promise for sediment concentration measurements in certain environments and concentration ranges include dielectric sensors (Starr et al., 2000), 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 USDA–ARS Walnut Gulch experimental watershed in semi-arid southeastern Arizona.

This USDA–ARS facility has a long history of developing approaches to assessing sediment concentration, transport, and yield (Renard et al., 1993; Lane et al., 1992; Renard and Laursen, 1975; Libby, 1968). Although constrained to small flow events by traversing slot method limitations, Libby (1968) showed that bed load transport remains high throughout the progression of runoff events despite the tailing off of water flow rates in the later part of the hydrograph.

Starr et al. (2000) reported on the measurement of soil particle concentrations in suspension using a dielectric method. Based on the principles of time domain reflectometry (TDR; Topp et al., 1980), the difference between the dielectric constant of water (approx. 80) and that of soil sediment particles (approx. 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, that is, the real refractive index (n), and assuming negligible electromagnetic dispersion, sediment concentration can be determined. Here, n is defined as the ratio of the speed of light in a vacuum to the speed of electromagnetic propagation through a substance. A simple linear equation for sediment concentration can be derived (ignoring bound water effects) using a linear mixing model:

\[ C = \frac{\rho_s(n - n_w)}{(n_s - n_w)} \]  

(1)

where C is concentration (g L$^{-1}$), \( \rho_s \) is the mass density of sediment solids (g L$^{-1}$), n is the measured refractive index in runoff waters, \( n_w \) is the refractive index of water at a given temperature, and \( n_s \) is the refractive index of solids (Starr et al., 2000). The value of \( n_s \) can be set equal to 2, \( \rho_s \) set equal to 2.65 (10$^3$) g L$^{-1}$, and \( n_w \) calculated given the measured temperature using an empirical equation (Weast, 1986):

\[ n_w = \left[ 78.54(1 - 4.58(10^{-3})(T-25)) + 1.19(10^{-5})(T-25)^2 - 2.8(10^{-8})(T-25)^3 \right]^{1/2} \]  

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where T is temperature (°C).

It would be advantageous to develop a method for measuring sediment concentrations in situ for the large flows from the watershed, with possible future application to other environments. Persson and Berndtsson (1998) described a probe with sensing rods embedded in hard non-conducting plastic, which they used for measuring soil water content on the soil surface. Hypothetically, this basic design can be adapted for insertion in the base of a flume for basal sediment concentration measurement in large, violent monsoon flows. The objective of this article is to describe this new method. As an example application, the time progression of basal sediment concentration through a flume during large-scale monsoon events was determined. To accomplish this, the probe was first calibrated and its performance validated in the laboratory using sediment materials from the site in a range of size classes. It was then used to monitor basal concentration during three monsoon flows that varied in peak discharge and duration.

MATERIALS AND METHODS

The TDR probe has three 55 cm long stainless steel rods with square cross-section embedded (press fit into machined slots) in a 2.5 cm thick slab of Delrin plastic. A Tektronix 1502B cable tester was coupled to the probe via coaxial cable. The probe was calibrated to read \( \rho \) by recording TDR effective length readings on the cable tester (Topp et al., 1980) in air and water. The calibration line was determined by linear regression done using air \((n = 1)\) and water \((n = 8.56\) to 9.35) at a range of temperatures \((T = 1.7°C\) to 40°C). This procedure eliminates the effects of the Delrin plastic so that \( \rho \) of the water/sediment mixtures could be determined and concentration calculated from equations 1 and 2. The root mean square error (RMSE) of this calibration line and the deviations between known and measured sediment concentrations, when expressed as an equivalent concentration, gave an indication of the error that can be expected with the method. Similarly, the standard deviation of repeated measurements in water and water/sediment mixtures at room temperature was used to estimate the minimum change in concentration that can be detected with a single measurement (resolution).

A calibration chamber was constructed for mixing and measuring different sediment concentrations (fig. 1). Pulverized silica powder (<250 µm maximum diameter) and water were mixed to known concentrations for comparing the sensor readout with a known standard (Starr et al., 2000) that simulates soil sediment. Fine sediment from a runoff retention pond at the site was sieved to a maximum diameter of 250 µm and used to validate the performance for fine particle sizes. The concentration was measured immediately (within a few seconds) following mixing in the chamber. During the measurement interval, no sediment could be seen accumulating at the base of the chamber. Turbulent conditions in the chamber existed for a short period following mixing, and particle settling over the measurement interval was assumed to be negligible. A rectangular box was placed over the sensor, sealed, and filled with bed material from the channel at known concentrations and size ranges to validate the sensor response for particle sizes up to 2.5 cm.

For the field application, the probe was embedded in the center of Flume 6 (Renard and Laursen, 1975; Libby, 1968) upstream from the stilling well intake that was used for flow depth measurement and subsequent flow discharge determination (fig. 2). The probe was installed flush with the base to provide in-situ measurements while avoiding flow disturbances, cavitations, and direct impact from rocks. Persson and Berndtsson (1998) showed that the sensor was insensitive to depth changes greater than about 2 cm. Testing of simulated flow depth vs. sensor output (fig. 2) was conducted to validate the measurement volume and determine minimum practical flow depth for the probe. Sediment concentration and discharge were monitored during three runoff events occurring in early August 2000. These represented small, medium, and large-scale events. Flow temperature was measured at the edge of the flow periodically using a thermometer. One can readily see the difficulty with traditional flow sample extraction given the violent conditions (fig. 3) of the largest flow event (August 11, 2000) shown near its peak discharge.

RESULTS AND DISCUSSION

Based on the laboratory tests, the known \( \rho \) of air and water at a range of temperatures was plotted versus measured effective probe length to derive a calibration for absolute \( \rho \) determination (fig. 4). The regression analysis (fig. 4) of 14 data points showed a coefficient of determination \((r^2)\) of 0.998 (fig. 4), indicating a high degree of linearity in the sensor’s response. Using equation 1 to estimate the equivalent concentration errors associated with the (RMSE of 0.090 gives a value of 0.031 kg L\(^{-1}\) at 25°C. The rapid cooling/
warming and wide temperature range may have contributed to the observed errors in these data through expansion or contraction of the probe materials.

Sensor concentration readings for silica powder mixed in the calibration chamber and channel bed sediment of various size ranges were in good agreement (fig. 5) with oven-dried gravimetrically measured concentrations. Data were grouped around the line \( y = x \), as would be expected, but the deviations from ideal behavior were much greater for the channel bed sediments than for the sediment and water mixtures. The greatest deviation was for the \(<0.2 \text{ cm}\) size class, for which the sensor overstated actual concentration by \(0.18 \text{ kg L}^{-1}\). The bed material concentrations were quite high because these measurements were static tests of a probe completely covered in sediment. For the sediment and water mixtures, the greatest deviation was for silica powder, where the sensor understated actual concentration by as much as \(0.022 \text{ kg L}^{-1}\).

The system was able to discriminate much smaller changes in sediment concentration than either the RMSE of the air/water calibration or the deviations of the sensor from gravimetric readings. Repeated measurements of \(n\) in pure water and buried sediment at room temperature had a standard deviation averaging 0.005 (\(n\) is a unitless quantity), which corresponds with a resolution limit of 0.002 kg L\(^{-1}\) at 25°C. Without sediment-specific calibration, the absolute accuracy of the method cannot be expected to be better than 0.02 to 0.03 kg L\(^{-1}\) for sediment and water mixtures, and considerably lower for 0 to 2.5 cm channel bed material. Thus, application of the method for absolute concentration determination will be limited to high-concentration environments. In a controlled laboratory environment where only changes in concentration are required, much lower concentrations can be studied (Starr et al., 2000).

Simulated flow tests where depth of water over the probe was varied (data not shown) indicated that as flow depth increased from 0 to 2 cm, \(n\) readings increased rapidly. Flow depth increases beyond 2.5 cm depth had no effect on sensor output. Thus, the probe must be a minimum of 2.5 cm below the water surface to prevent air entry into the measurement volume. Persson and Berndtsson (1998) showed that the measurement volume of this probe does not extend beyond around 2 cm from the probe face. With a measurement depth of around 0 to 2 cm near the center of the flume, the probe was situated to measure maximum flow concentration, as sediments gravitate to the base and center.

Basal concentrations during the large (130 m\(^3\) s\(^{-1}\)), intermediate (70 m\(^3\) s\(^{-1}\)), and small (5 m\(^3\) s\(^{-1}\)) peak discharges (fig. 6) showed a similar progression throughout the hydrograph. Basal concentration was highly variable during the rising limb of the hydrograph and peaked at a relatively stable plateau following peak flow, where it remained throughout much of the tail before falling in the final stages of the events. For the large and intermediate events, basal concentrations reached maximum values (1.5 to 1.9 kg L\(^{-1}\)) that were comparable to the laboratory values for a completely covered probe. During the falling limb of the hydrographs at the site, transported bed sediment shifts to smaller particle sizes, sand dunes may form, and channel erosion rates are high (Libby, 1968). Dune formation on top of the probe might explain the exceedingly high concentrations observed. While dune formation will occur in the channel, the flume has a greater
pitch and is designed to minimize or eliminate sediment deposition. Another possible explanation is that hyperconcentrated flow was occurring at the bottom center of the flume. For the small flow event, basal concentrations were lower (0.2 to 0.8 kg L⁻¹).

Near the peak discharge of the large event, rocks and what sounded like boulders could be heard striking the intake plate of the stilling well. The effect of large rocks landing on the probe and associated uneven mixing of the basal sediment may have contributed to the high variability observed in the rising limb and peak. This was followed by a swishing that sounded like sand during the plateau phase when there was lower variability in measured concentrations. A shift to smaller particle sizes can generally be expected as flow discharge gets lower, and might be related to the decrease in concentration variability as the flow progressed. There may be additional measurement errors associated with particle sizes larger than 2.5 cm. In future tests, it would be desirable to construct laboratory vessels capable of assessing larger channel materials.

Because the measurements were highly localized at a single point at the base and center of the flume, no inferences can be made at this time as to how homogeneous the concentration profile is. However, TDR technology is available in various probe types with the possibility of measuring many probes sequentially, and there is reason to believe that this technology could be adapted for improved sediment concentration measurement in the future. Future developments might include probes that would extend up into the flow for the purpose of obtaining depth profiles. For instance, a more traditional three-prong TDR probe might be held parallel to the flow direction and raised/lowered to established depths or held at an angle for integrating over a range of flow depth.

If sediment fluxes are desired (and they generally are in erosion research), an independent assessment of flow velocity will be necessary with the TDR method, as would be the case for other automated methods of sediment concentration measurement. If future advances are to be achieved, careful consideration should be given to use probe designs appropriate for the flow conditions under study. Experimentation under less violent flow conditions than those in this study would be advantageous. One possibility is to directly measure flow velocity at or near the probe. Another possibility is to indirectly calculate or model the flow velocity. For example, running a narrow rod/wire down the center of a metal pipe forms a coaxial waveguide for TDR that could be used to measure concentrations in the pipe. However, volumetric flow rates in the pipe would have to be independently assessed to obtain sediment discharge rates. This might be achieved through a measurement of pressure differential across the pipe or by using a Doppler ultrasonic flowmeter.

**CONCLUSIONS**

A system for measuring runoff sediment concentrations in situ was developed based on the principles of time domain reflectometry. The model sensor output and the calibration for absolute n determination in air and pure water suggested a linear response. Without sediment-specific calibration, deviations between known and measured concentrations
were within 0.02 kg L\(^{-1}\) for sediment and water mixtures and within 0.2 kg L\(^{-1}\) when the probe was completely covered in 0 to 2.5 cm channel material.

A probe was constructed and characterized for sediment concentration measurement in the base of a flume at the USDA–ARS Walnut Gulch experimental watershed. The probe was installed in a large flume at the site and used to monitor sediment concentrations during three events with large (130 m\(^3\) s\(^{-1}\)), intermediate (70 m\(^3\) s\(^{-1}\)), and small (5 m\(^3\) s\(^{-1}\)) peak discharges. Basal concentrations during the rising limb of the hydrograph were highly variable and reached a relatively stable plateau following peak discharge, where they remained throughout much of the tail before falling in the final stages of the events. For the large and intermediate events, basal concentrations reached maximum values (1.5 to 1.9 kg L\(^{-1}\)) that were comparable to the laboratory values for a completely covered probe. For the small flow event, basal concentrations were lower (0.2 to 0.8 kg L\(^{-1}\)). The exceedingly high concentrations measured during the plateaus could be explained by either dune formation or hyperconcentrated flow at the base. These observations suggest a period of high sediment transport and channel erosion in the tail of monsoon runoff hydrographs that would be consistent with previous observations. The dielectric method provides in–situ measurements in high concentration and bed transport environments where traditional methods fail. However, in low–concentration environments, instrumentation errors in absolute concentration measurement may exceed the limits of error tolerance.

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**References**


