New Field Method to Determine Streamflow Timing Using Electrical Resistance Sensors

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ABSTRACT

Electrical resistance (ER) sensors were constructed to monitor streambed saturation to infer ephemeral streamflow timing. The sensors were evaluated in an ephemeral stream through comparison with temperature-based methods, a stream gauge, and soil water content sensors. The ER sensors were more accurate at estimating streamflow timing and the resultant data required less interpretation than data from temperature-based methods. Accuracy was equivalent to timing methods using stream gauge and soil water content measurements. The ER sensors are advantageous for use in ephemeral stream channels because they are inexpensive, deployable above or below the sediment surface, insensitive to depth, and do not require connecting wires to an external datalogger or power source. On the basis of these results, we conclude that ER sensors may be used to monitor changes in soil water content within the vadose zone. Additionally, the sensors can be used to infer the presence of surface water in diversion canals, storm-water sewers, and in the form of overland runoff.

GIVEN THE ERRATIC and variable nature of ephemeral and intermittent streamflow in arid and semiarid basins, long-term collection of streamflow timing is necessary for obtaining information on extreme flow events and seasons. Streamflow timing in channels and arroyos is used to accurately model fluid transport through the unsaturated zone beneath ephemeral streams and to constrain channel recharge estimation, a primary component of aquifer replenishment. Additionally, streamflow timing is a necessary component for designing storm-water and flood-control networks in flood-prone environments.

Current methods used to estimate streamflow timing include flow-rated stream gauges, velocity meters, soil water content sensors, and temperature sensors (Latkovich and Leavesly, 1993; Constantz et al., 2001; Blasch et al., unpublished data). These methods have met with varying success depending upon channel morphology, bed sediment characteristics, frequency and duration of streamflow, and other requirements (e.g., magnitude of temperature signal).

Stream gauges and velocity meters accurately determine streamflow timing, but generally are not suitable for ephemeral channels that experience changes in channel morphology (Tadayon et al., 2000). Stream gauges and velocity meters installed at the bed sediment surface can become buried or damaged by moving sediment or debris. Consequently, streamflow timing sensors deployed within the vadose zone have been shown to be advantageous under these circumstances (Constantz et al., 2001).

Soil water content methods detect infiltration and percolation of water through the sediments, which may be used to infer timing of streamflow (Blasch et al., unpublished data). Placing sensors in the subsurface reduces the possibility that they will be damaged or lost during flow. Logging instrumentation, however, must be placed on or near the bank with cables extending to the buried sensors.

Temperature methods enable inference of streamflow timing on the basis of the combined transport of heat and fluid within the bed sediments (Constantz and Thomas, 1996, 1997; Ronan et al., 1998; Constantz et al., 2001). Recent development of small (<10 cm^3), inexpensive, waterproof temperature sensors with integrated data storage enable measurement and storage of temperature values without the need for external connecting wires. This advantage enables in situ temperature monitoring in ephemeral channels with unstable beds over large areas with high spatial resolution.

While temperature methods have been used successfully to monitor the timing of streamflow in ephemeral channels, the methods have limitations. Specifically, certain conditions are required for streamflow to produce a readily identifiable thermal signal. For example, water with the same temperature as the channel will not produce an identifiable signal. In ephemeral stream channels subject to repeated scour and deposition, changes in sediment surface elevation complicate the application of numerical methods used for interpretation of the temperature data.

In this investigation, we converted commercially available temperature sensors into ER sensors to monitor water content and tested their utility for streamflow detection. Advantages of the ER approach include functionality above or below the channel surface, functionality in all streamflow temperatures, lack of connecting wires, and minimal interpretation of data. These same attributes necessary for streamflow timing are also advantageous for monitoring sediment saturation in other similar vadose zone applications such as irrigated fields, fluctuating water tables, and postburn environments.

BACKGROUND AND THEORY

An electrical resistance measurement in a porous medium can be idealized as a measurement of three resistances in series: the bulk electrical resistance of the medium, which includes solid grains and pore water, (R_m), and a contact resis-

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Abbreviations: ER, electrical resistance [sensors]; PVC, polyvinyl chloride; TDR, time domain reflectometry.

tance at each electrode or medium interface (R_c [two electrical contacts in the circuit]). Summation of the three resistances in series results in the total electrical resistance, R_t:

$$R_t = R_c + R_m + R_c \qquad [1]$$

Bulk Electrical Resistance of a Porous Medium

The bulk electrical conductivity (S m^{-1}) of a porous medium, σ, is a measure of the sediment's and pore water's ability to transmit electrical current. The inverse of electrical resistivity (resistance per unit length) is electrical conductivity. Archie (1942) developed an empirical relation between bulk electrical conductivity, pore-water electrical conductivity (S m^{-1}), σ_w; sediment-surface electrical conductivity (S m^{-1}), σ_s; and sediment saturation (vol. water/vol. pores), S:

$$\sigma = \sigma_w S^n + \sigma_s = \frac{1}{R_m} \qquad [2]$$

where n is a unitless constant that is specific to the sediment type and distribution. For unconsolidated materials, n is approximately 2 (Archie, 1942).

Pore-water electrical conductivity is a measure of a solution's ability to transmit an electrical current and is dependent upon the number of ions present in the solution and their associated charge. Pore-water electrical conductivity is also directly proportional to solution temperature. Sediment-surface electrical conductivity is the ability of the sediments to transmit an electrical current and is primarily dependent upon the clay content of the sediments (McNeil, 1980). In many hydrologic settings of interest, pore-water electrical conductivity is much higher than the sediment-surface electrical conductivity. Because the electrical conductivity of air is practically zero, the electrical conductivity of a medium is strongly dependent on the extent to which it is saturated with water. The normalized electrical conductivity, σ_n, shows a nonlinear dependence on saturation (from Eq. [2]):

$$\sigma_n = \frac{\sigma - \sigma_s}{\sigma_w} = S^n \qquad [3]$$

Generally, the electrical conductivity of a coarse-grained medium will be lower than that of a fine-grained medium at the same water soil water potential because the finer-grained material will have a higher water saturation.

Contact Resistance

The inverse of contact resistance, contact conductivity, is the ability of an electrode in a circuit to pass an electrical current to the porous medium. High contact resistance is caused by air-filled gaps (i.e., pores) that exist between the electrodes and the sediment grains (Fig. 1). Because of the relatively high electrical conductivity imparted by solutes to pore water, water-filled pores produce low contact resistances. A small diameter pore requires a more negative soil water potential to drain than a large diameter pore. The pores adjacent to an electrode will tend to be smaller in fine-grained materials than in coarse-grained materials. As a result, contact resistance is lower in fine-grained materials than in coarse-grained material at the same soil water potential.

Total Electrical Resistance and Streamflow Timing

At the onset of an ephemeral streamflow event, water rapidly percolates into the sediment pores and replaces air. As the saturation at a given depth increases, the bulk electrical conductivity of the medium increases as well. An ER sensor, however, will not measure a significant change in electrical conductivity until a continuous electrical circuit is supported between the electrodes. The level of saturation required for a continuous circuit is defined as the contact resistance thresh-

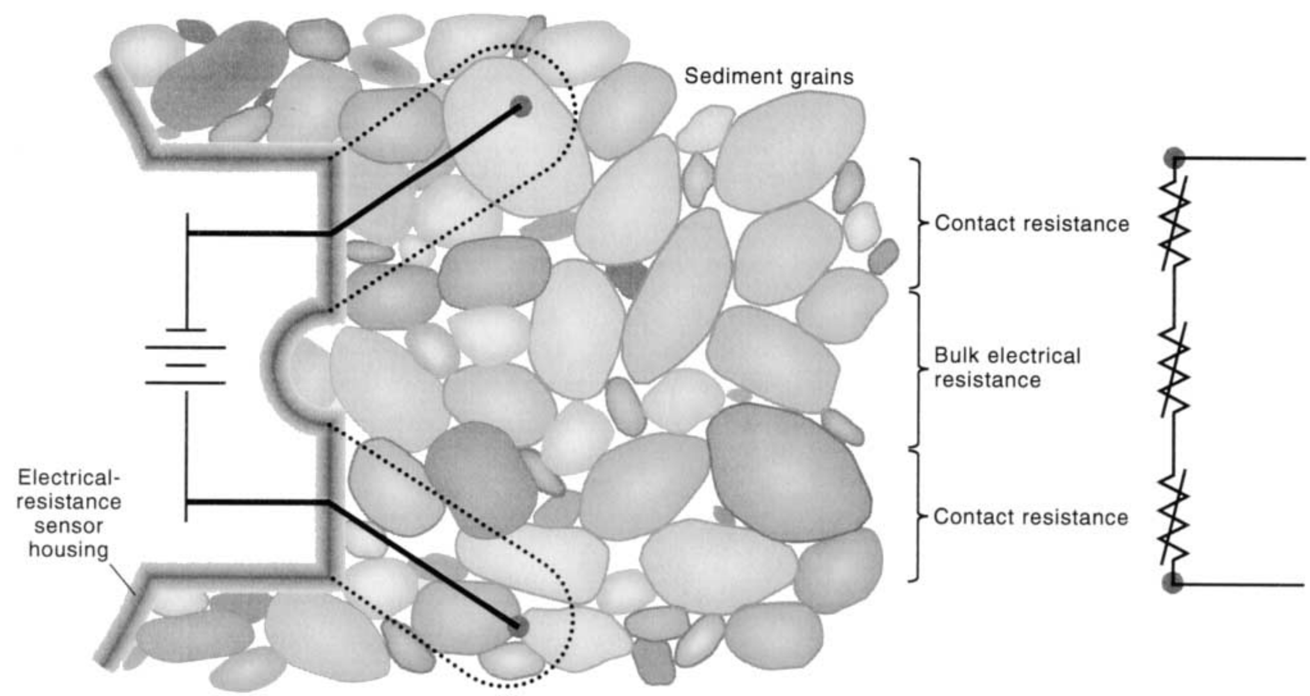


Fig. 1. Schematic presentation of bulk electrical and contact resistances of a sediment medium. Dotted lines surrounding the wire leads denote the critical region for determining contact resistance. The remaining regions outside the dotted lines are important for determining the bulk electrical resistance. A measurement of electrical resistance is a combined measure of the bulk electrical resistance of the medium and contact resistance.

old. This occurs when saturation of the medium in contact with the electrodes produces a negligible resistance. As the pores near the electrodes and the pores in the bulk medium continue to fill with water, the total electrical conductivity increases to a maximum at full saturation (i.e., maximum pore-water content). Under these saturated conditions, the total electrical conductivity will vary as the pore-water electrical conductivity or the bulk medium temperature fluctuates.

The cessation of streamflow is accompanied by drying of the sediments and a reduction in saturation, causing a decrease in the total electrical conductivity. An ER sensor will show a decline during drying until the contact resistance threshold of the medium surrounding the electrodes is reached, which is marked by a rapid decrease in the measured total electrical conductivity to zero. The soil water potential at which the medium in contact with the electrodes reaches its contact resis-

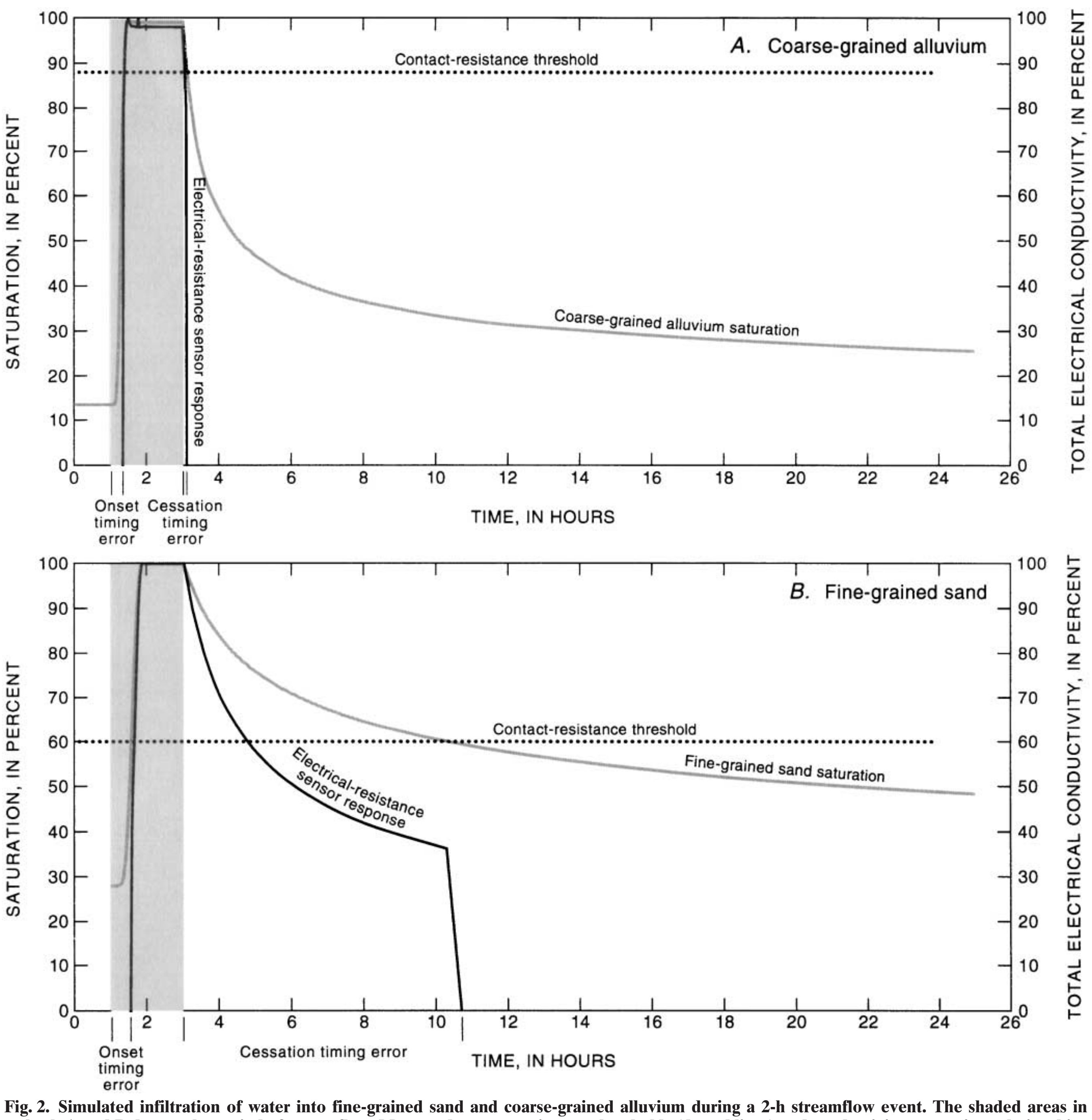


Fig. 2. Simulated infiltration of water into fine-grained sand and coarse-grained alluvium during a 2-h streamflow event. The shaded areas in both A and B denote the period of streamflow. Measured contact resistance thresholds (dotted lines) and conductivity–saturation relationships were used to calculate saturation and normalized total electrical conductivity measurements at 0.2 m. (A) The saturation response (light solid line) and electrical resistance sensor response (dark solid lines) within the coarse-grained alluvium to the infiltration event and redistribution. (B) The simulated saturation and electrical resistance response for a sensor in fine-grained sand. The onset timing error is defined as the difference in time between the onset of a streamflow event and the activation of the electrical-resistance sensor. The cessation timing error is defined as the difference in time between the end of the streamflow event and the deactivation of the sensor. Both types of error are shown in A and B.

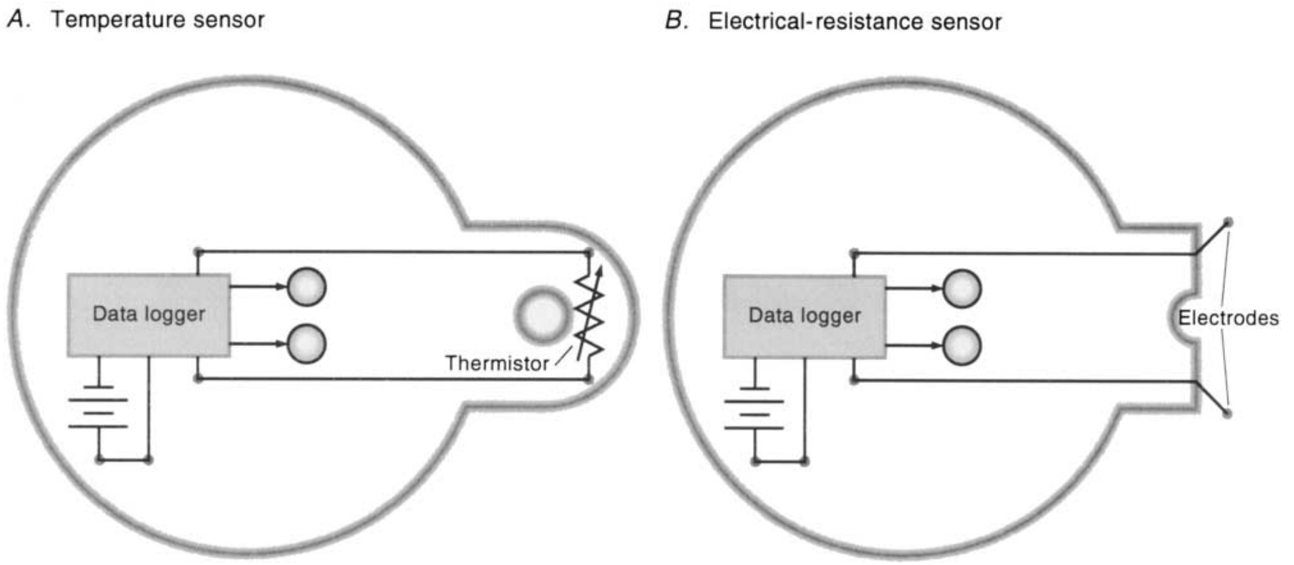


Fig. 3. Schematic diagram of a temperature sensor: (A) before modification; (B) after conversion to an electrical-resistance sensor through removal of the thermistor.

tance threshold is not always equivalent to the air-entry pressure of the medium. The contact resistance threshold will only occur at the air-entry pressure of the bulk medium if the pores adjacent to the sensor electrodes are equivalent to or greater in size than the largest pores in the bulk medium. If the pores near the electrodes are smaller than those in the bulk medium, then the contact resistance threshold will occur at a lower potential than the air-entry pressure of the bulk medium.

Observed changes in saturation at a given depth lag behind the onset and cessation of streamflow because of the time required for a wetting front to reach a given depth or for drainage and evaporation to affect the soil water content at this depth (Blasch et al., unpublished data). This lag increases with depth of observation. At the onset of a streamflow event, the time lag is a function of the hydraulic properties of the sediments and the antecedent water content. Generally, lag times are shorter for coarse sediments and for sediments having high antecedent water contents. At the cessation of flow, the time lag is a function of hydraulic conductivity of the sediments, pore-water redistribution at depth, and evapotranspiration demands.

The advance of a hypothetical wetting front through fine-grained sands and coarse-grained alluvium was modeled using the sediments' contact resistance thresholds determined in column experiments (described in the results) and the sediments' hydraulic properties determined by Fleming (2001) and Hoffmann et al. (2002). A hypothetical streamflow event was simulated to examine possible differences that may be observed in the field between timing of streamflow arrival at the surface and advancement of the infiltrated water at depth. A variably saturated flow model, HYDRUS 1-D (Simunek et al., 1998), was used to simulate the advance of the wetting front, a period of saturated flow, and subsequent drainage. Saturation values were simulated at a depth of 0.20 m in response to a 2-h streamflow event (Fig. 2). Flow was modeled as a constant flux upper boundary with an infiltration rate of 10 cm h^{-1}. The initial pressure head was −50 cm throughout the profile. The simulated timing of the streamflow event at 0.20 m depth that would be inferred from ER sensors is also shown.

The onset timing error is the difference in time between the arrival of the streamflow event at the surface and the start time inferred by the ER sensor. The cessation timing error is the difference between the end of the streamflow event and the cessation as indicated by the ER sensor. The magnitudes of the onset and cessation timing errors are dependent upon the contact resistance threshold value, the hydraulic conductivity of the sediments, antecedent water contents, and depth of the sensor. The effect of the contact resistance threshold on streamflow timing error is noticeable in these simulations. For the coarse-grained alluvium, the soil water potential of the contact-resistance threshold is similar in magnitude to the air-entry pressure of the bulk medium. Thus, the ER response declines to zero as soon as the sediments begin to drain. In comparison, the water potential associated with the contact-resistance threshold for the fine-grained sand is much lower than the air-entry pressure of the bulk medium, resulting in a decrease in total conductivity before the sharp decrease associated with drainage of the medium around the electrodes. If the timing of this sharp drop is used to identify the end of flow, the timing error will be greater during drainage. To reduce this timing error, the time recorded by the ER sensor as the initiation of drainage should be used. This will require an additional step in the analysis of the data.

MATERIALS AND METHODS

Column experiments were designed to quantify the saturation dependence of the ER sensor output. Field experiments were designed to compare the capabilities of ER sensors with different methods for estimating streamflow timing.

Stowaway TidbiT temperature sensors (Onset Corporation, Bourne, MA) were modified for this study.[1] These sensors contain a thermistor, onboard datalogger, and battery encapsulated in a 10-cm^3 plastic housing. The thermistor used has a temperature range of −20 to 50°C with a precision of approximately 0.1°C.

The TidbiTs were modified by removing the thermistor and stripping the insulation enclosing the electrodes (Fig. 3). The average distance of separation between the two electrodes at the housing surface was approximately 0.5 mm. The electrodes were cut to varying lengths ranging from 0.01 mm to approximately 4 mm. The electrodes were bent at a 45° angle to prevent contact with each other. During installation in the

[1]Mention of brand names does not constitute endorsement by the U.S. Geological Survey or the University of Arizona.

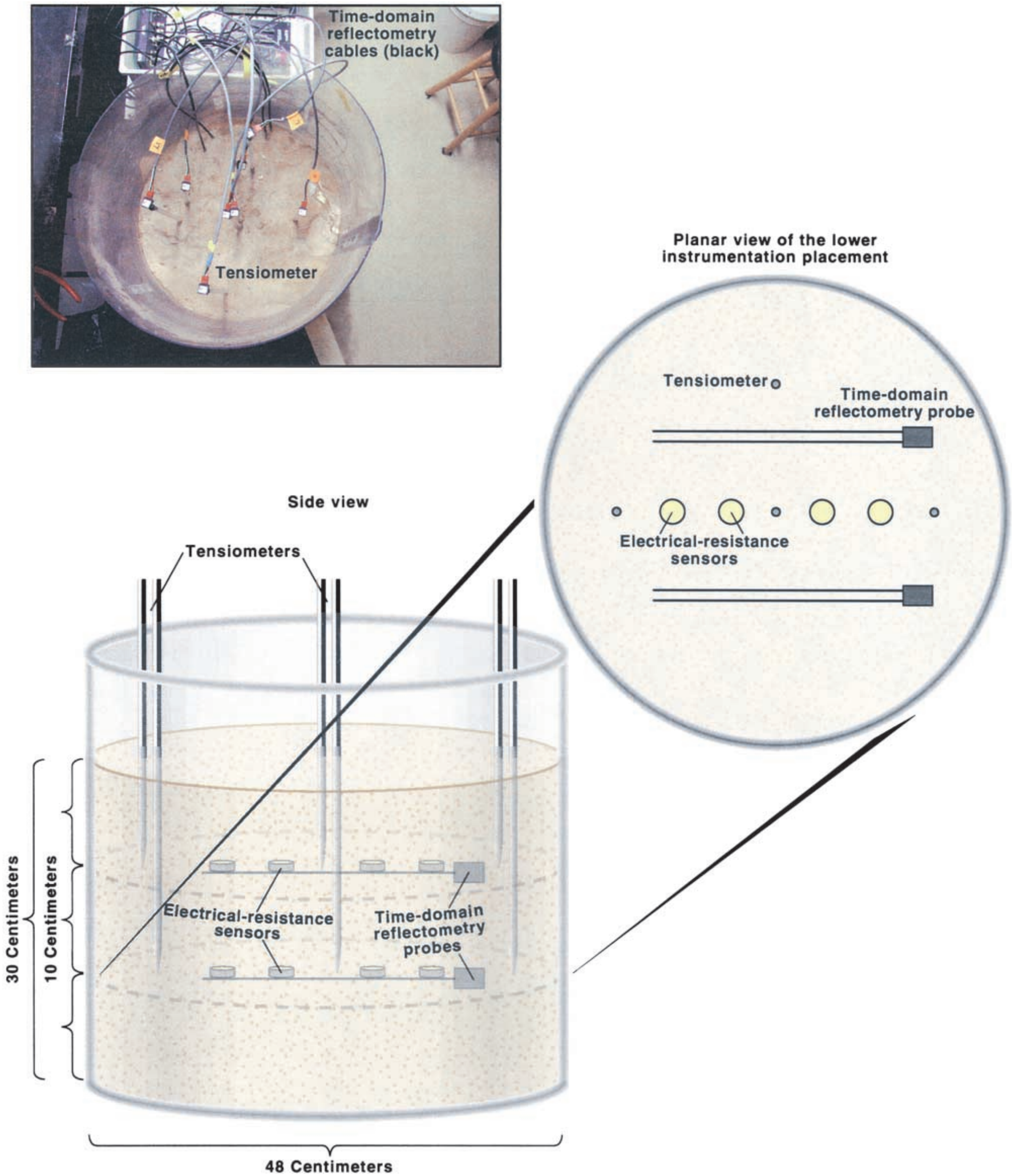


Fig. 4. Photograph and schematic diagram of the sensor locations within the laboratory column used to measure the contact-resistance threshold for the fine-grained sand and the coarse-grained alluvium.

subsurface, sediment was placed surrounding the electrodes. This was accomplished by lightly sifting the sediment over the ER sensor to ensure coverage of the electrodes.

Column Experiments

The two objectives of the column experiments were (i) to evaluate the ER sensor response during imbibition and drying and (ii) to quantify contact resistance thresholds for two sediment types. The first sediment was Vinton fine-grained sand (sandy, mixed thermic Typic Torrifluvent). The second sediment was coarse-grained alluvium from Rillito Creek (36.2% gravel, 55.2% sand, 8.6% silt and clay). Circular 48 cm diameter by 50 cm tall columns were packed to a bulk density of 1.34 g cm^{-3} (Fig. 4). Columns were instrumented with four horizontal time domain reflectometry (TDR) probes, eight tensiometers, and eight ER sensors. The two-rod TDR probes were 20 cm long, and a distance of 3 cm separated the TDR rods.

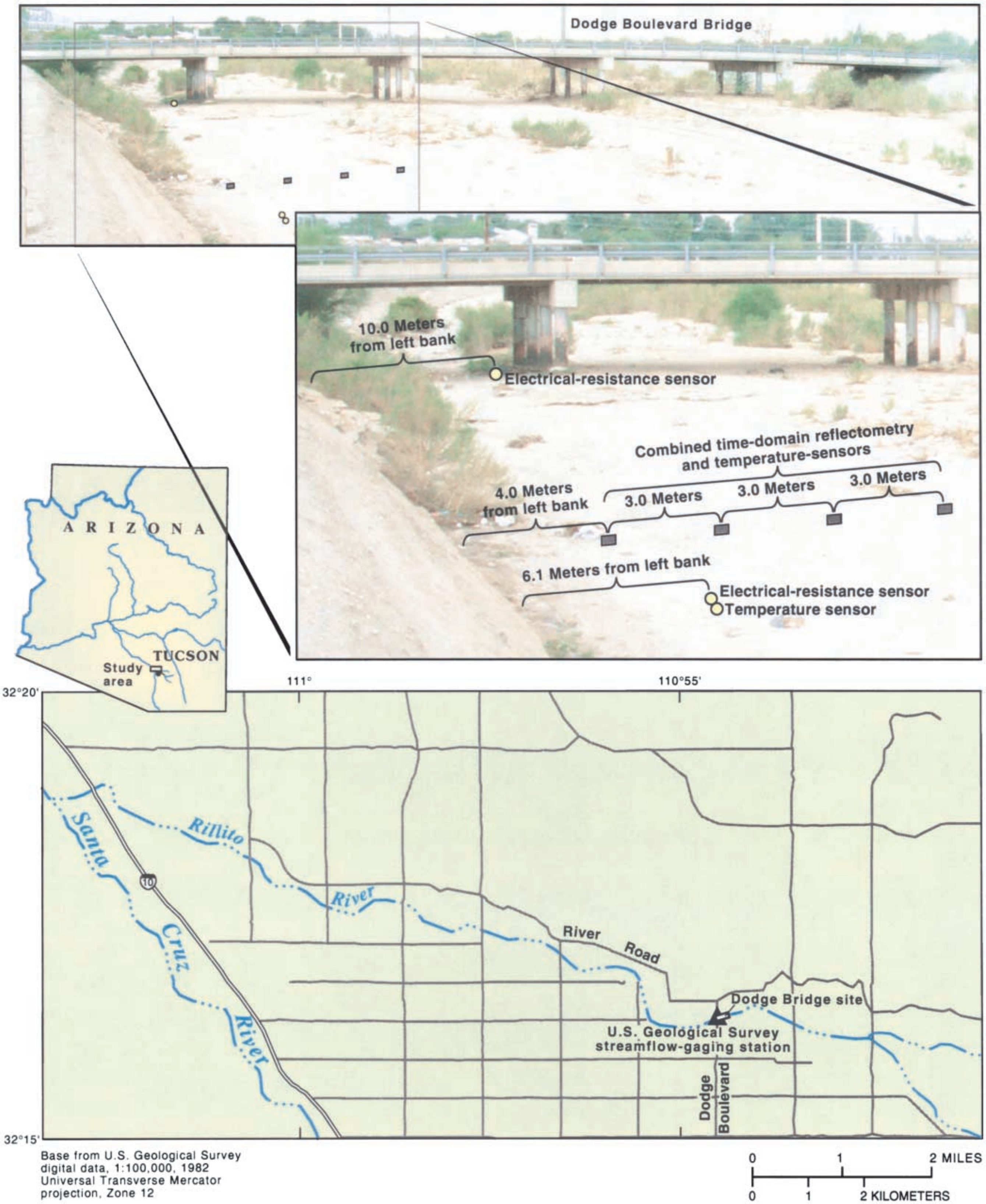


Fig. 5. Sensor locations deployed in Rillito Creek, Tucson, AZ.

Table 1. Contact resistance thresholds in fine-grained sand and coarse-grained alluvium.

	Contact resistance thresholds (%)				
Soil type	Low	High	Mean	Standard Deviation	Samples *n*
Fine sand	39	91	60	20	16
Coarse alluvium	81	99	88	5.0	44

Two TDR probes were placed horizontally at 10 cm depth and the remaining two rods were placed at 20 cm depth. Four ER sensors were placed between the TDR probes at each depth. Four tensiometers were placed at each depth. The column was wetted repeatedly from either the top or bottom with tap water (conductivity = 447.3 $\mu S\ cm^{-1}$) until 5 cm of water was ponded above the soil surface. The ponded condition was maintained for approximately 20 min, and then the column was allowed to drain. The columns remained undisturbed until the TDR probes indicated that the saturation of the soil was similar to that at the start of the experiment.

Ephemeral Channel Experiment

Electrical resistance sensors were installed above and below the sediment surface in Rillito Creek, an ephemeral stream on the north side of Tucson, AZ, in the same native coarse-grained alluvium used in the column experiments (Fig. 5). Rillito Creek is typical of ephemeral streams in the arid and semiarid southwestern United States. During most of the year, the stream is dry; however, after prolonged or intense periods of rainfall and/or snowmelt, streamflow can exist for several hours to several days along its 20-km length. The aboveground sensors were bolted inside a 5 by 12 cm polyvinyl chloride (PVC) tube to protect against surface abrasions. The PVC tube remained open at both ends, and about 30 3-mm-diam. holes were drilled into the sides to ensure water flow into the container and to prevent the accumulation of clay and silt particles within the protective enclosure. Three ER sensors were attached to a U.S. Geological Survey stream gauge (gauging station 09485700; Tadayon et al., 2000) above the channel surface. To avoid interference with stream-gauge operation, the sensors were installed 3 to 5 cm below the stream-gauge orifice line. Two additional sensors were deployed 15 cm below the streambed surface within 6 m of a row of four TDR probes having specifications similar to those used in the column experiments. The sensors were installed without the protection of the PVC tube to improve soil–sensor contact. The sensors were attached to a PVC plate and cabled to a rebar stake. The sampling frequency was 5 min for the sensors, 2 min for the TDR probes, and the stream gauge operated by the U.S. Geological Survey recorded streamflow data every 15 min.

Stream-gauge and TDR data were post-processed in a similar manner. Timings of flow events were inferred when the stream-gauge values were greater than zero and volumetric water content values exceeded 0.30 $cm^3\ cm^{-3}$. The onset of streamflow was inferred from the ER data when the conductivity values exceeded zero. The cessation of streamflow was identified as a decrease in total electrical conductivity caused by a dewatering of the media. For surface ER sensors, this decline was immediate and the values dropped to zero. For the subsurface sensors, the initiation of drainage caused a significant drop in total electrical conductivity, but not always to a zero value. The total electrical conductivity did not drop to zero until the contact threshold was reached. However, the initial decline in conductivity signifies the beginning of dewatering and was recorded as the cessation time. This reduced the cessation timing error as described in Fig. 2.

Two temperature sensors were installed at different depths in the bed sediments within 3 m of the ER sensors for comparison of the temperature method with the electrical-resistance method. A temperature sensor was installed 1.0 m below the sediment surface, a depth determined by Blasch et al. (unpublished data) as optimal for inferring streamflow timing at this study site. A second TidbiT temperature sensor was installed 0.05 m below the sediment surface. Both sensors measured and recorded bed sediment temperatures at 5-min intervals. The thermographs were post-processed using a 1-h moving standard deviation.

RESULTS

Column Experiments

Electrode lengths were tested repeatedly in column experiments and during ephemeral streamflow events

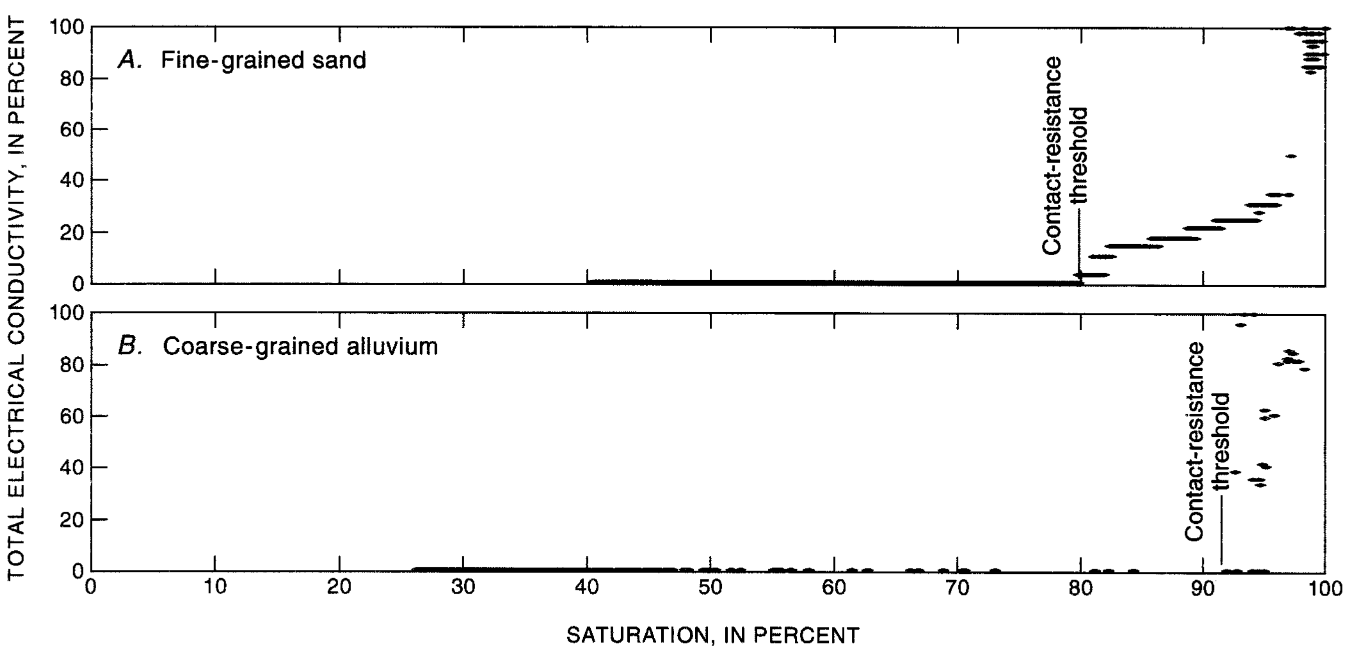
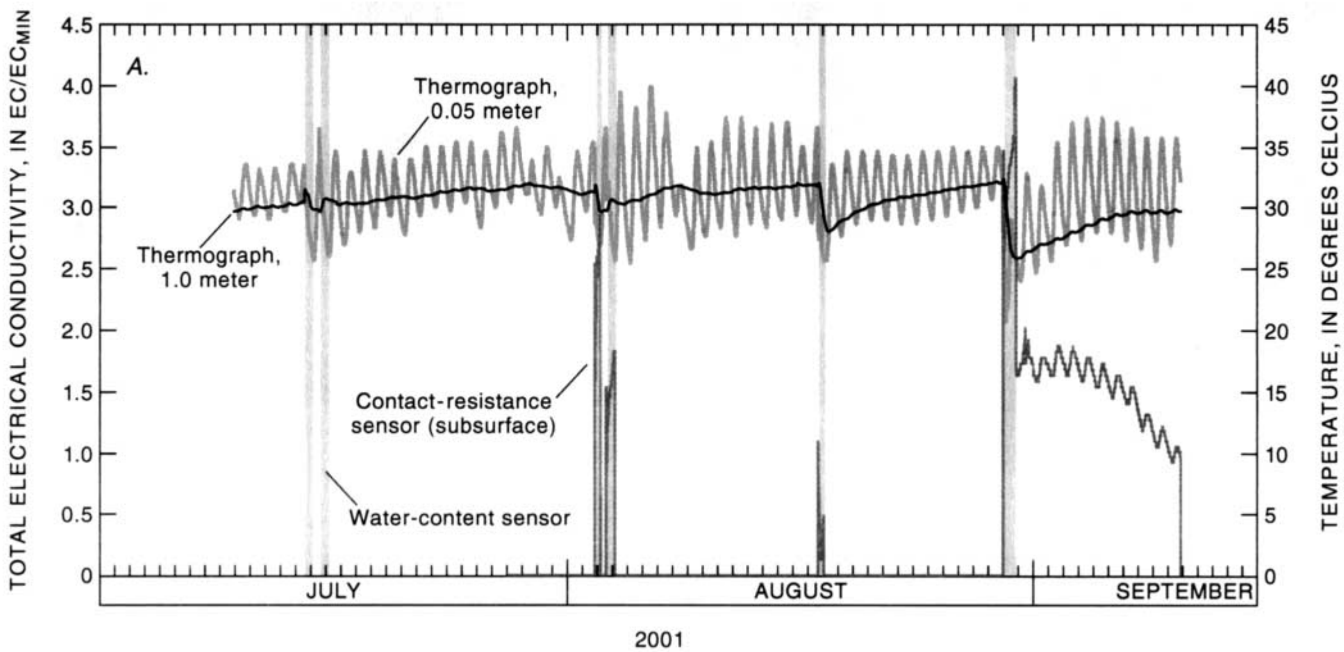


Fig. 6. Total electrical conductivity in relation to saturation as determined in column experiments for one of the sensors. (A) Fine-grained sand. (B) Coarse-grained alluvium. Note the higher contact-resistance threshold for the coarse-grained alluvium.



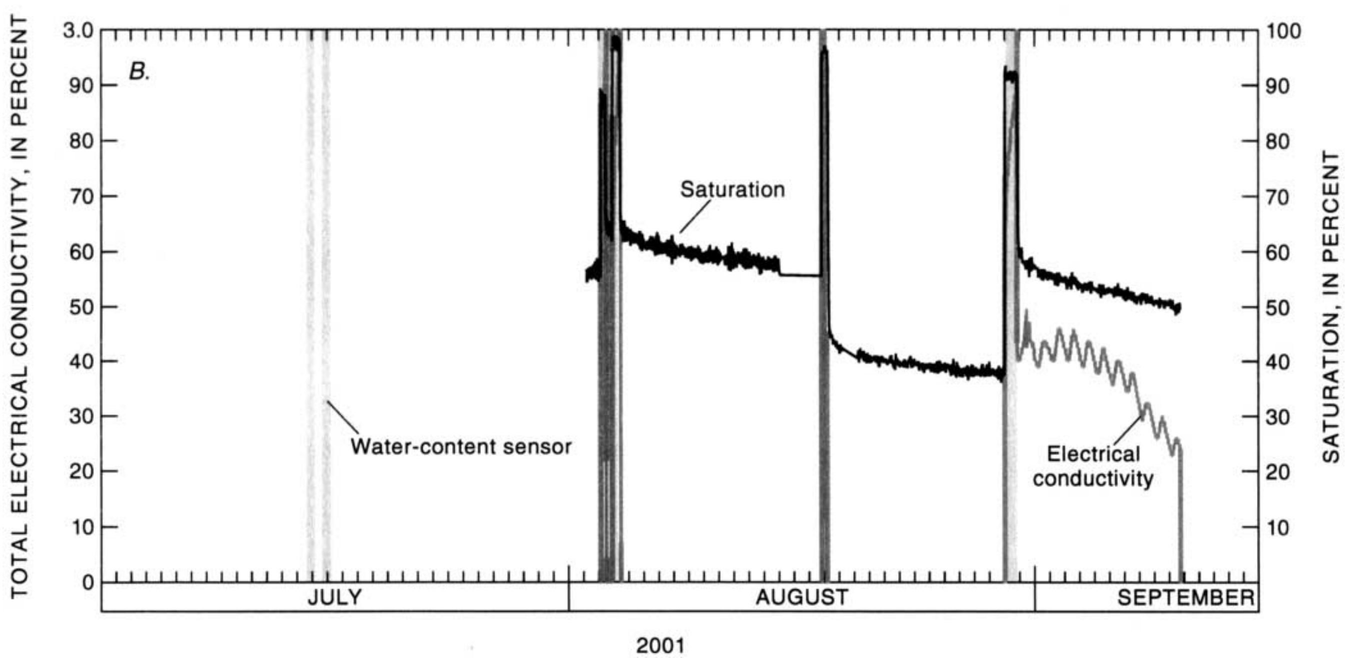


Fig. 7. (A) Electrical conductivity as measured by an electrical-resistance sensor positioned 0.15 m below the ground surface and temperature responses measured at depths of 0.05 m and 1.0 m. The subsurface electrical-resistance sensor was installed 28 July 2001, after the first two streamflow events. (B) Electrical conductivity as measured by an electrical-resistance sensor positioned 0.15 m below the ground surface and saturation as measured by the water content sensors. The shaded areas denote periods of streamflow as inferred using measured soil water content data.

in Rillito Creek near Tucson, AZ. A minimum electrode length of 3 mm was required for reliable detection of streamflow conditions. Shorter electrode lengths on sensors installed above the bed sediment surface did not detect all of the streamflow events. Longer electrode lengths in the subsurface provided increased contact with the surrounding media, resulting in a lower contact resistance threshold than ER sensors with shorter electrodes. Electrode lengths between 3 and 4 mm were considered optimal for measuring conductivity both above and within the alluvial sediments.

Contact resistance thresholds for the coarse-grained alluvium and fine-grained sand were estimated from the column experiments. Contact resistance thresholds for coarse-grained alluvium and gravel ranged from 81 to 99% and averaged 88% saturation (Table 1). For the Vinton fine sand, the threshold ranged from 39 to 91% and averaged 60% saturation. The large range for the Vinton fine sand may reflect the differences between the sample volumes of the TDR sensors and the ER sensors. A comparison of the measured total electrical conductivity for one sensor tested in both Vinton fine

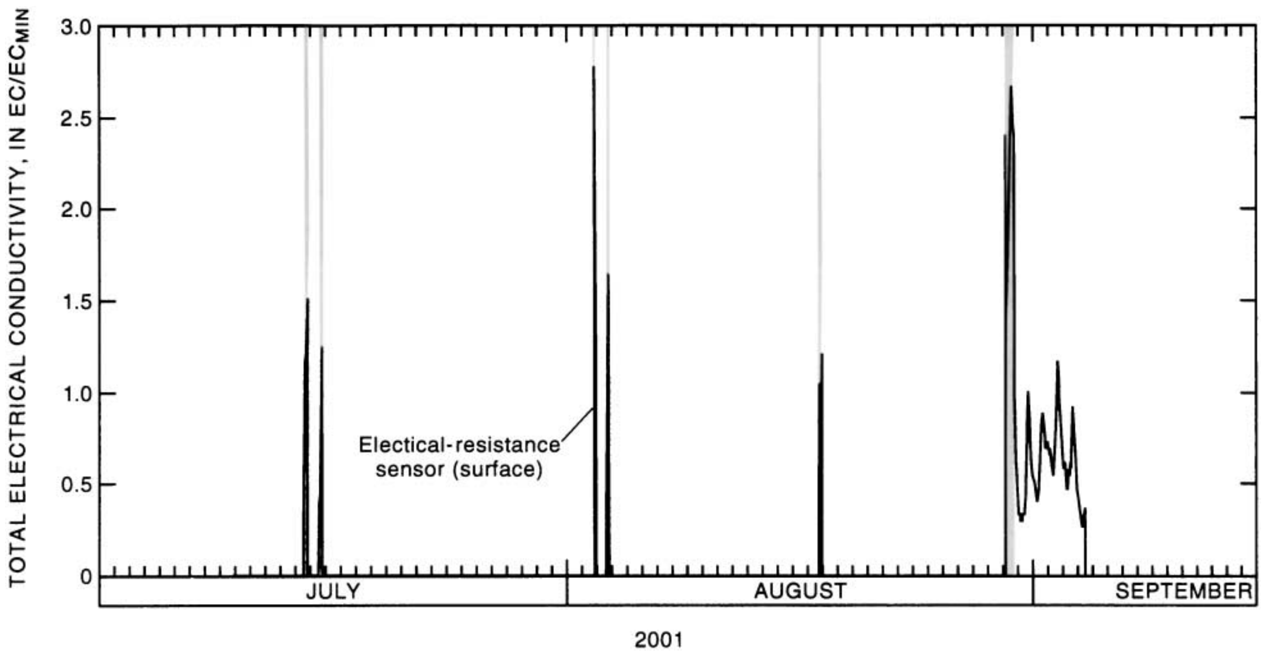


Fig. 8. Electrical conductivity as measured by an electrical-resistance sensor positioned at the surface. The shaded areas denote periods of streamflow as measured by a U.S. Geological Survey streamflow gauge.

sand and coarse alluvium is shown in Fig. 6. The measured contact resistance thresholds for each sediment type were the same for increasing and decreasing saturation. No hysteresis was observed.

Ephemeral Channel Experiment

Electrical conductivity data were collected in Rillito Creek from 10 July to 10 Sept. 2001 by ER sensors placed above the streambed surface and from 28 July to 10 Sept. 2001 by sensors placed 0.15 m below the streambed surface. From 10 July to 10 September, there were six streamflow events. Each event was less than 24 h in duration. Conductivity data from the ER sensors above and below the sediment surface clearly identified the streamflow events (Fig. 7 and Fig. 8). Streamflow timing inferred by the ER sensors was compared with timing from the alternate methods, including stream-gauge methods, temperature methods, and soil water content methods. Because of the variability in streamflow path, locations of the sensors, and sediment deposition and erosion, it was difficult to determine an absolute best streamflow-timing method. Instead, the comparisons were used as a relative means to evaluate the streamflow-timing methods under similar streamflow conditions.

Comparisons of the onset and cessation errors between the streamflow-timing methods are displayed in Table 2. The subsurface-temperature method and electrical-resistance method identified the onset of flow, on average, within 11 min of the arrival of the streamflow event as identified by the soil water content method. At the cessation of flow, however, the temperature method was less accurate than the electrical-resistance method. At a depth of 1.0 m, the temperature method identified the cessation of flow, on average, 108 min before the true cessation of flow as identified by the soil water content method. The temperature sensor at 0.05 m underestimated the duration of streamflow by 568 min. These errors were attributed to the short durations of the flow events resulting in minimal changes to the diurnal temperature patterns except at the onset of flow. In comparison, the electrical-resistance method identified the end of flow approximately 72.5 min after the soil water content sensors identified the end of flow. A comparison of two water content sensors 9 m apart, but transverse

Table 2. Streamflow timing errors at the onset and cessation of flow using the temperature method and the electrical-resistance method. Negative values indicate the method identifies flow preceding the timing of streamflow measured using a conventional method (stream gauge for surface timing and soil water content [TDR] for subsurface timing).

	Error							
	Temperature sensors (0.05-m depth)†		Temperature sensors (1.0-m depth)†		Electrical resistance sensors (0.15-m depth)†		Electrical resistance sensors (surface)‡	
	Onset	Cessation	Onset	Cessation	Onset	Cessation	Onset	Cessation
	min							
Mean	−7.31	−568	−19.8	−108	3.88	72.5	−12.1	70
Standard Deviation	6.74	118	48.5	250	7.02	40.3	13.4	60

† Timing of streamflow compared with conventional method (soil water content measurements).
‡ Timing of streamflow compared with conventional method (stream gauge measurements).

to the flow path, yielded a difference in onset timing of 5.5 min and a cessation timing difference of 88 min. We speculate that these timing differences are a consequence of the heterogeneity of the sediments.

Measured field values of saturation and electrical conductivity shown in Fig. 7 are comparable in appearance to those shown in the modeling exercise of Fig. 2 for coarse-grained alluvium. The measured contact resistance threshold ranged from 82 to 91% saturation and averaged 88%. During the final event, a 5- to 10-cm layer of silt and clay was deposited on the bed sediment surface. Silt and clay percolated into the sediments and were found with the sediment matrix surrounding the ER sensors. Consequently, dewatering of the sediments differed from the previous events by displaying two contact resistance thresholds: one for the larger pores of the matrix associated with the alluvium and a second for the pores associated with the silt and clay. The authors interpret the dewatering as a two-stage process and cessation of flow occurring at the first threshold. The second threshold occurred at a saturation value of 49%. The diurnal fluctuations in the conductivity values are attributed to the diurnal change in temperature within the porous media.

The surface ER sensors estimated the timing of flow, on average, 12.1 min before the stream gauge and estimated the cessation of flow, on average, 70 min after the stream gauge (Table 2). This discrepancy is probably the result of the ER sensors being installed at an elevation of about 3 to 5 cm below the stream-gauge orifice line. At this position, they were triggered at a slightly lower stage than was recorded at the stream gauge. The errors should decrease significantly if the stream-gauge ports and ER sensors were placed at the same elevation. During the final event, about 5 to 10 cm of fine silt and clay were deposited on top of the surface ER sensors. The layer of silt and clay deposited around the sensor electrodes produced a slower decrease in saturation compared with earlier events (Fig. 8).

Streamflow-timing errors for the subsurface and surface methods show little difference at the onset of a streamflow event. Infiltration of water into the near surface sediments is rapid at the onset of flow. The difference in cessation timing, however, is the critical factor for overall duration timing accuracy. The electrical-resistance method is more accurate than the temperature methods. Analysis of the surface electrical-resistance data and the stream-gauge data required the least amount of effort to identify streamflow conditions because the methods record zeros during no-flow conditions and nonzero values during the presence of streamflow. The water content data and subsurface electrical-resistance data required more analysis time to account for travel time of the wetting front and initiation of drainage. Finally, the subsurface method using the temperature data required the most effort to analyze, even when using the automated moving standard deviation method.

DISCUSSION

Correct installation of the ER sensors is important for decreasing streamflow detection errors. The sensors are most accurate when placed above the stream channel surface to avoid the influence of sediments and to reduce analysis requirements. Caution must be taken when selecting the height of sensor placement. Sensors placed too low can be buried by deposited sediments (Fig. 8). If a sensor is placed too high, however, it may fail to detect streamflow at low stages. Sensors placed in the subsurface should be as close to the sediment surface as possible to reduce streamflow-timing errors, while minimizing the risk of sensor damage or removal.

Comparison of the maximum electrical conductivity measured for the streamflow events both above and below the bed surface indicates changes in the electrical conductivity of the water during each event. The variability in magnitudes is attributed to changes in temperature and conductivity of the water; however, these values were not measured.

CONCLUSIONS

Small, inexpensive, resistance loggers can detect saturated conditions and infer streamflow timing. Estimates of streamflow timing were more accurate when made using the ER sensors rather than the temperature methods and were comparable in accuracy to stream-gauge and soil water content methods. Advantages of ER sensors include depth independence and reduced analysis requirements. The low cost, ease of implementation, and absence of datalogger connecting wires from the sensor to the stream bank provides a distinct advantage over conventional methods.

Electrical resistance sensors can be used to determine the presence of surface water in ephemeral and intermittent stream channels, storm-water sewers, diversion canals, and in the form of overland runoff. The sensors also can be used to identify the occurrence of saturated soil conditions in the vadose zone, for example, changing water levels, bank storage near streams, and movement of irrigation water in agricultural fields.

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