DETECTING MACROPORE FINGERING USING TEMPORAL ELECTRICAL RESISTIVITY IMAGING

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**Collection
Research**

HIGHLIGHTS

- Single macropores can be detected using temporal electrical resistivity imaging under controlled conditions.
- Macropore flow can be detected based on preferentially wetted fingers of increased conductance.
- Macropore activation does not appear to require saturated surface conditions to induce preferential flow.

ABSTRACT. Riparian soils are uniquely susceptible to the formation of macropores, which are hypothesized to promote fast transport of water and contaminants through upper soil layers. Electrical Resistivity Imaging (ERI) can locate spatial heterogeneities in soil wetting patterns and evaluate differences due to vegetation, thus optimizing the design of riparian buffers. Temporal ERI (TERI) imaging was conducted in a fine and coarse field setting with artificial macropores to evaluate flow under unsaturated simulated rainfall conditions and saturated infiltrometer conditions. While single macropores are detectable using TERI datasets, the results in an average field setting would detect the wetted area surrounding a macropore, not the macropore itself. The results were similar for both the primary fine grain soil site in Oklahoma as well as the coarse grain site in North Carolina. TERI data indicated that without artificial conditions with low noise conditions, a single macropore would not be detected, a wetted zone would be the best detection. In ordinary field evaluation of natural macropores, the TERI technique would detect the wetted zone around a macropore similar to a high hydraulic conductivity zone in a heterogeneous soil matrix. Finally, the results confirmed that macropore activation does not require saturated conditions to generate preferential flow.

Keywords. Hydrogeophysics, Preferential flowpaths, Riparian buffers, Temporal electrical resistivity imaging.

Modern agricultural practices use fertilizers and pesticides that may be transported from fields to adjacent streams during precipitation events, resulting in negative impacts to surface water. Riparian buffers are vegetation strips that offer streams and other surface water reservoirs protection from the contaminant runoff (Edwards et al., 1988; Hill, 2019). Simply creating larger buffers zones is not ideal for stopping the most runoff because it creates a land productivity issue (Weiler and Naef, 2003b; Lee et al., 2004; Tiwari et al., 2015). Thus, it is vital to determine size and location to place the buffer zone to satisfy both runoff prevention and optimal land productivity. Knowing the hydrogeological properties

of geological features such as macropores and gravel outcrops would increase the efficacy in determining buffer zone dimensions (Weiler and Naef, 2003a; Miller et al., 2014; Hester and Fox, 2020).

The current design of conservation practices, such as vegetative filter strips and riparian buffers, focuses solely on surface runoff with subsurface nutrient transport assumed to be negligible (Fox, 2019). However, subsurface transport can become significant with preferential leaching and can negate the intended benefits of these widely adopted control practices (Fuchs et al., 2009). In fact, when observing the functioning of riparian buffers, the hydrologic response of the system often suggests a much higher infiltration capacity than expected based on soil texture or matrix infiltration experiments alone (Sabbagh et al., 2009; Heeren et al., 2015). To limit degradation of ecosystem services and improve resource use efficiency, research is needed on understanding and incorporating the influence of preferential flow in buffer design (Orozco-Lopez et al., 2018; Fox, 2019).

It is difficult to classify a macropore based on a predetermined size because of soil heterogeneity. For this reason, the definition of a macropore is a pore that exhibits preferential

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Submitted for review on 3 September 2020 as manuscript number NRES 14294; approved for publication as a Research Article and as part of the Preferential Flow and Piping in Riparian Buffers Collection by the Natural Resources & Environmental Systems Community of ASABE on 16 March 2021.

channeling of fluids in comparison to other pores in the surrounding strata (Beven and Germann, 1982). This preferential channeling has made computer modeling of macropore flow historically problematic. According to Jarvis et al. (1991) and Christiansen et al. (2004), the largest uncertainty with modeling macropore flow remains the behavior changes between saturated and unsaturated upper-boundary conditions. Apart from saturation, soil type and heterogeneity are major compound factors for preferential flow in macropores. This was indicated in the studies on tillage in fields, which have shown the concentrations of dissolved phosphorus in precipitation event water was much greater in no-till fields (Williams et al., 2016). Disturbing the soil can help reduce the risk of phosphorus transport from tile-drained fields. In places that cannot be tilled, especially near any adjacent stream to a field, mapping the area for preferential flow paths can aid runoff prevention efforts using riparian buffers.

Both soil texture and soil moisture content impact the occurrence and prevalence of preferential flow in soils (Simunek et al., 2003; Orozco-Lopez et al., 2018). Preferential flow has been observed to occur in a variety of soil textures. For example, a meta-analysis performed by Koestel et al. (2012) on the impact of macropore flow on solute breakthrough curves suggested that moderate macropore flow was only possible above a threshold of 8% clay content. Macropore flow has also been observed to generate at near saturation, proposed by some authors to be -10 to -6 cm when the water pressure exceeds the required entry pressure of the pore interface (Jarvis and Larsson, 2001; Jarvis, 2007). Furthermore, the interaction of this macropore flow with the presence of a shallow water table may also be of more importance for riparian buffers (Orozco-Lopez et al., 2018). The presence of a shallow water table can modify soil water contents in the vadose zone providing greater opportunities for the activation of macropore flow and reduces mass transfer between the matrix and macropore domains. While recent research has suggested that preferential flow pathways can be activated under unsaturated soil moisture conditions, additional research to verify the occurrence of preferential flow under various soil hydraulic conditions and an understanding of how to detect preferential flow once it activates is critical.

Temporal electrical resistivity imaging (TERI) is a geophysical surveying technique used for evaluating the subsurface. Resistivity measurements have been used since the 1800s to evaluate electrical changes in the subsurface (Van Nostrand and Cook, 1966). Advances in instrumentation and computing allowed temporal resistivity data to be acquired and processed to observe soil fluid movement and lateral migration (Griffiths and Turnbull, 1985; Halihan et al., 2019). While resistivity measurements have existed for a long time, TERI was limited in soil studies prior to sufficient instrument and computational developments (Jung et al., 2000; Zhou et al., 2001). As the instrumentation has become more widely available, the differences in resistivity due to the migration of soil moisture have been evaluated for a number of soil properties, most commonly vegetation, water content, and temperature variability (Jayawickreme et al., 2008; Acharya et al., 2017; Dick et al., 2018; Halihan et al., 2019).

By being able to define particular soil properties that can change over the time period of the resistivity data set collection, significant insights can be gained into the spatial location and temporal period of soil moisture migration and macropore activation.

One goal of macropore studies is to determine the distribution of macropores in the subsurface. From distribution, we can quantify flow and transport to determine best management for areas with significant macropore flow. Using TERI may allow macropore structure to be delineated by observing where preferential flowpaths occur as the electrical properties change more quickly in areas affected by macropores (Moysey and Liu, 2012; Menichino et al., 2014).

The objective of this research is to evaluate in controlled conditions whether TERI can demonstrate the presence of artificial macropores whose location and dimensions are known *a priori*. Using sites with fine grained and coarse grained soils, TERI was used to determine if artificial precipitation or artificial infiltration in a single macropore could be detected. The signal generated from the wetting may either be too weak to be detected compared to background noise or may be too similar to signals generated by soil heterogeneity.

SITE DESCRIPTION

For thorough examination of preferential flow in differing upper-boundary conditions, our experiments were conducted at two field sites. The first site was in Stillwater, Oklahoma (36°06'04.25"N, 97°08'11.01"W). Stillwater has ~89 cm (35 in.) of precipitation annually with average high temperatures of 34°C (94°F) during the summer and mild to cool winters, where temperatures regularly drop below freezing (Zhang and Nearing, 2005; Mullens et al., 2013). The soil surface in the region is characterized by a Grainola-Lucien complex soil and the Permian Garber-Wellington formation lies beneath (Cobb and Hawker, 1918; Lim and Miller, 2004). Grainola-Lucien complex soils are defined by their clay-like appearance and texture. The fine-grained nature of the soil yields limited lateral flow, which should indicate higher preferential flow in macropores. Within the survey area, the ground was relatively flat with 24 cm (9 in.) total relief and covered with Bermuda and fescue grasses, commonly seen throughout Oklahoma. Rooting depth was measured on site, ranging from 8-10 cm (fig. 1a).

The second field site was in Raleigh, North Carolina (35°45'36.36"N, 78°40'44.79"W). Raleigh has a similar humid-subtropical climate to Stillwater, differing with more annual precipitation of 117 cm (46 in.) (Boyles and Raman, 2003). This site contrasts with the site in Stillwater exhibiting a Pacolet sandy loam at the surface and Late Proterozoic-Cambrian lineated felsic mica gneiss beneath (Cawthorn, 1970). The coarser grain size demonstrated the presence of macropores and a higher slope for the site allowed for more preferential pathways and lateral flow than the Oklahoma fine-grained soil. The survey area consisted of bare soil to lightly vegetated woodland on the periphery (fig. 1b). Vegetation in the area included Loblolly pine, red maple, oak genus, butterfly bushes and holly. The plot was adjacent to a

Figure 1. Field sites for TERI experiments. 28 electrodes at 0.4-m spacing were utilized for the experiments. A) ERI line in fine grain soil site in Oklahoma. Orange cable connects 28 stainless steel electrodes at a 1.6-m spacing in fine soil. Field location in Oklahoma indicated in inset map. B) ERI line in coarse grain soil site in North Carolina. The orange cable was used to generate the dataset utilized for this work. The white cylinder below the sprinkler tripod is the rain gauge used for measuring precipitation. Inset map indicates field location in North Carolina.

tributary to Walnut Creek, a small-first order stream. According to the USGS 0208734795 streamflow station at South Wilmington St. [1.6 km (1 mile) from North Carolina field site], the discharge for Walnut Creek averaged 38 m³/s (1340 ft³/s) in 2019. The average width of the stream is 5.9 m (19 ft).

For the set of experiments conducted to evaluate macropores with TERI, the majority of work was conducted at the Oklahoma site. This site allowed better control of soil moisture changes by providing a slower moving moisture front with well constrained grassy vegetation. The North Carolina site provided a reasonable comparison as the experiments only used artificial precipitation and macropores. This eliminated the variability that would be generated due to macropore structure, precipitation patterns, and riparian vegetation effects. The only requirement of the experimental sites was to provide a different soil hydraulic conductivity. A site with extremely electrically resistive soil (quartz sand with no fines) may impact the results if data quality decreased due to poor electrical coupling. Additionally, a site with significant quantities of roots or hardpan would make it difficult to insert artificial macropores.

METHODS

The design of the field experiments involved determining a set of soil and macropore parameters and scale for the experiment using TERI. We present the field design followed

by the design of the ERI setup. Three methods were used to generate electrical changes by adding fluids to macropores, and these wetting approaches are detailed. Finally, the set of TERI experiments are presented followed by the methods used to analyze the results.

EXPERIMENTAL FIELD DESIGN

To determine if TERI would detect a macropore via electrically conductive fingering patterns, a series of field tests were conducted to compare ERI resolution, fluid boundary conditions, and macropore dimensions. An electrically conductive finger pattern should appear as a stripe or streak of increasing bulk electrical conductivity on a TERI dataset. These increases in bulk electrical conductivity in the TERI data are the primary focus to indicate fluid pathways provided by macropores. Different wetting approaches were used to separately test saturated and unsaturated upper-boundary conditions (table 1). A macropore infiltrometer gradually drained water directly into an artificial macropore and emulated saturated conditions. The same area was allowed to reach steady state for a couple of hours and was wetted again with a sprinkler simulating rainfall over a larger area, which maintained unsaturated upper-boundary conditions. The artificial macropores were also limited in number and distributed evenly across the line. This was to avoid signal blending from multiple macropores during data processing.

Table 1. Imaging sequence for the TERI experiments in Oklahoma and North Carolina.

Field Site	Test	Soil Type	Upper-Boundary Conditions	Electrode Spacing (m)	Wetting Approach
Fine Soil (Okla.)	1 macropore	Fine	unsaturated	0.4	metal rod
				0.8	
				1.6	
				1.6	2 L water
				0.8	
				0.4	
	3 macropores	Fine	unsaturated saturated	0.4	20 L water
				0.8	
				1.6	
Coarse Soil (N.C.)	1 macropore	Coarse	unsaturated	0.4	sprinkler
			saturated		macropore infiltrometer

ERI Design

A series of ERI resolution tests were conducted to determine the electrode spacing for maximum temporal dataset quality. ERI experiments rely on a point source approximation for the location of electrodes. Thus, getting them too close violates the basic assumptions for ERI data collection and limits electrode spacing in the field to about 0.25 m on a practical basis (Van Nostrand and Cook, 1966). On the other end of the spacing scale, too large of spacings would compromise the ability to detect macropore signatures and the signal strength would decrease with increasing image block size (fig. 2). In the first experiment, three overlapping ERI lines with electrode spacings doubling for subsequent experiments were set up along a flat grassy area in the Oklahoma field site. Testing sizes ranged from 0.4-, 0.8-, and 1.6-m spacings. Artificial macropores were placed in the middle of each line spacing. The macropores were located at 5.3, 11.0, and 20.4 m. Following data collection, the field apparent resistivity data are inverted to generate a modeled resistivity profile (Loke et al., 2003). Regardless of inversion approach, an ERI dataset becomes a smoothed representation of the subsurface variations in electrical properties.

ERI datasets were collected with an AGI SuperSting R8 Resistivity Instrument. The instrument allows a user to collect and store full apparent resistivity datasets. Multiple datasets can be processed to evaluate the changes in bulk resistivity that occurred between datasets to obtain TERI data. A relay switch box and a 28-electrode dumb cable were attached to stainless steel electrodes to survey the field site. To power the instrument for data collection, a gas-powered generator and an AGI power supply box were used to convert the 110 V source from the generator to a 12 V source for the instrument. Once the survey lines were laid out in the field, the SuperSting field computer measured apparent resistivity between electrodes using the Halihan/Fenstemaker

method (Halihan et al., 2005; Acharya et al., 2017; Halihan et al., 2019). A robust inversion technique was utilized to convert the apparent resistivity data to modeled electrical resistivity data. These data were differenced in order to obtain datasets of changes in bulk electrical conductivity between datasets (Halihan et al., 2011; Acharya et al., 2017; Halihan et al., 2019).

WETTING APPROACHES

In the Oklahoma field site, a metal rod with a diameter of 6 mm was placed in the middle of the ERI line to a depth of 50 cm (fig. 1). The metal rod was left *in situ* during imaging to simulate a high salinity fluid filling a single macropore. The importance of this technique lies with the lack of lateral spread with a metal rod in the ground versus wetting the ground with water. The same metal rod was used to generate additional artificial macropores.

Once the artificial macropores were created, they were wetted in an attempt to only impact the zone influenced by the artificial macropores. At both sites, a 5-gal bucket was utilized to make a macropore infiltrometer. A hole the diameter of the rod was put in the bottom of the bucket; by holding the bucket down over the macropore location, water could be added directly to the macropore. A full infiltrometer would take approximately 30 min to an hour to drain into the macropore. This setup allowed partial wetting of the macropore domain with a limited volume of water. In these experiments, we used 2 or 20 L of water to fill the infiltrometer. The setup also allowed imaging of the macropore under fully saturated conditions by continually adding water during an imaging period. The flow rate from the infiltrometer was measured by monitoring the change in water level over time in the bucket and using the hole size for the flow area.

The final wetting method used a sprinkler on both sites to wet the survey area while avoiding any pooling of water at

Figure 2. Setup for field TERI experiments. A) Location of processed data nodes after inversion of TERI datasets relative to the location of the artificial macropore and the electrodes for a 0.4-m spacing experiment. B) Field photo of Stillwater, Okla., field site with metal rod used to generate artificial macropore and simulate saline fluid in macropore. C) Schematic diagram of artificial macropores in field setting relative to entire TERI domain and 28 electrode setup.

the surface. A rain gauge was used to determine the precipitation flux generated by the sprinkler system. The sprinkler was applied to attempt to simulate a large precipitation event over an approximately 1-h period. The method may result in some uneven application of water due to the spray pattern of the sprinklers, but this did not result in visually significant differences in the wetted area. To monitor the soil moisture during the North Carolina experiments, EC-5 soil moisture sensors (METER Environment, Pullman, Wash.) were inserted at depths of 10, 20, 30, and 40 cm in covered trenches. EC-5 sensors have a measurement volume of approximately 0.2 L and therefore provide near point-scale estimates of water content. The sensors were connected to EM-50 data loggers (METER Environment, Pullman, Wash.), recording soil water contents at 1-min intervals. These sensors confirmed that soil moisture remained below saturation throughout the sprinkler infiltration tests.

IMAGING EXPERIMENTS

Data collection consisted of three experiments, with sets of imaging sequences where the ERI geophysical surveying was employed. The first imaging sequence involved determining the optimal ERI resolution for detecting a single macropore in the fine soil Oklahoma field site. The second imaging sequence was at the same field site with three macropores across the same ERI line in fine soil. The last and final imaging sequence was in the North Carolina field site, characterized by coarse soil.

For the Oklahoma field site, three electrode spacings of 0.4, 0.8, and 1.6 m were alternated between three electrical signal changes, totaling nine TERI datasets for the first sequence. Each signal detection was imaged once for each electrode spacing change. The first set of ERI datasets collected were three background datasets with no macropores, one for each electrode spacing. The first signal detection test was the metal rod left in place at the middle of the ERI line, while spacings were doubled for each of the three images. For the second test, the metal rod was removed from the ground, leaving an open macropore. In place of the metal rod, the macropore infiltrometer was placed and held over the macropore location. Water (2 L) was added to the macropore infiltrometer and allowed to fully drain into the macropore for the starting image set with the 2-L source. Finally, the last test in this imaging sequence was fundamentally identical with the second test, utilizing the macropore infiltrometer once more. This time, 20 L of water was added to the bucket, followed by the final three resistivity datasets being collected. There was an assumption that the wetted domain from a fluid addition would not migrate significantly during the time required to move cables and collect the three datasets at the varying resolutions.

TERI ANALYSIS

Once each ERI dataset was acquired from the field, they were numerically inverted and the datasets were differenced to determine the changes in bulk conductance over time (Hulihan et al., 2019). The RMSE (root mean square error) was evaluated for each ERI inversion and each TERI differenced dataset. The noise levels for the datasets were compared by evaluating two ERI datasets prior to any wetting experiments

to determine experimental repeatability of no water being added to the system. Once the noise levels were determined, the data could be evaluated as either an entire TERI dataset that was contoured by value as a 2D dataset or plotted along a line through the data as a 1D horizontal or vertical dataset. To compare different wetting methods, a single vertical or horizontal line of data were extracted from the TERI datasets to evaluate vertical or horizontal changes at the macropore locations.

The analysis to determine the effects of a single macropore first evaluated the effect of TERI resolution. The results of the various spacings were compared for the location of the metal rod. The effects of the various wetting methods were compared for the peak change in bulk conductance, how well the location and depth of the macropore was detected, and how much lateral signal was available from the various wetting sources. The second analysis involved three macropores evenly spaced over the ERI line to differentiate saturated versus unsaturated conditions. The unsaturated macropores affected by artificial precipitation were compared to the macropore that had saturated conditions throughout the experiment due to the macropore infiltrometer wetting a macropore during an entire imaging event. The final analysis compared the unsaturated and saturated macropores in the fine-grained Oklahoma site against the coarse-grained North Carolina site. The datasets were evaluated vertically at the location of the artificial macropore as well as comparing lateral extent.

RESULTS

The results present the overall data quality of the experiments; examining background noise levels required to detect macropore effects. First, the single macropore experiment with a range of TERI resolution and wetting sources is presented. Second, the multiple macropore experiment results are evaluated and then the third experiment is presented comparing between the coarse and fine-grained sites.

DATA QUALITY

At the Oklahoma site, there were 15 ERI datasets and 11 TERI datasets. The ERI inversion RMSE errors were approximately 2.5%. This was a low error percentage as RMSE can be as high as 20%-25% and still be considered acceptable ERI data (Zarroca et al., 2015). The TERI differencing datasets had lower RMSE differencing error values of approximately 1%. The changes in the difference data increased in the dataset over time in the shallow portion of the dataset as the ground heated up. This increased from less than a half percent change to approximately 2.5% increase in conductance (fig. 3). The background datasets for the TERI experiments indicated that less than 0.5% change in conductance was present between datasets due to instrumentation and setup.

The coarse-grained North Carolina field site included 3 ERI datasets and 2 TERI datasets. There was a higher error percentage among ERI datasets from North Carolina compared to datasets from Oklahoma, likely due to more electrically resistive soil conditions in North Carolina. ERI RMSE

Figure 3. TERI results of fine-grained Oklahoma experiment with two different wetting sources at 0.4-m electrode spacing. A) Metal rod source location indicated by black line. B) 20 L wetting source located at same lateral location as metal rod source. Note increase in noise from background data over time as data collection occurred after some ground heating occurred relative to the first wetting experiment.

error percentages were approximately 4.5%. TERI RMSE values were approximately 3%. Less heating occurred on the North Carolina site as it was better shaded than the Oklahoma site. The background datasets for the TERI experiments indicated that less than 0.5% change in conductance was present between datasets due to instrumentation and setup.

SINGLE MACROPORE DETECTABILITY

The effect of resolution from the single artificial macropore experiment provided the data to determine an effective electrode spacing for field investigations of natural macropores. The metal rod experiment provided a detectable signal of a 1.6% increase in conductance at the location of the rod in the 0.4-m electrode spacing dataset (figs. 3a and

4a). Data for 1D profiles (fig. 4) come from a single vertical line of data from the larger dataset (fig. 3). This was in a context of noise levels below 0.5% change in positive conductance and below ~1.0% noise levels in negative conductance. In typical field datasets with errors of 3% or higher, the rod would not be detectable in the 0.2-m block that the technique was evaluating, but in the low noise datasets, it was apparent. At the 0.8-m spacing, the rod was still detectable above the 0.5% noise level, but at the 1.6-m spacing the rod was part of the noise. The structure of the data has a negative change in resistivity of less than 1% as part of the signal. The depth of the rod was captured by the dataset as well with the bottom of the rod located adjacent to a peak value detected

Figure 4. Vertical profiles for single macropore resolution experiments with two different wetting sources. Gray zone indicates area interpreted as instrument and processing noise with level between -0.5 to 0.5% change in conductivity. A) Single metal rod simulating a saline macropore with no lateral flow away from the macropore. B) 20 L of water added to macropore to generate a wetted zone around the macropore to increase the conductance of the area.

just above or below the base (fig. 4a). The peak value trends deeper with larger image resolution.

The various wetting sources used for the single macropore experiment allowed larger signals to be generated as a greater volume of the subsurface became wetted. The 2 L source roughly doubled the signature from the metal rod with a peak conductance change of 2.9%. For the 2 L source, the 1.6-m spacing again could not detect the signal from the wetting relative to the noise in the dataset. For the 20 L source, the signal for the 0.4- and 0.8-m spacing increased to approximately 9%, and the 1.6-m spacing generated a change of approximately 3% allowing a detection relative to the noise of the datasets (fig. 4b). The peak values in the wetting sources tended to be at or near the surface with the gradient of the data dropping the value below the noise levels near the elevation of the bottom of the rod. The data also had negative changes in resistivity greater than the noise levels below the detection of the wetted area (fig. 4b). This was interpreted as an effect of the method and not a field change in the bulk conductance of the material.

On a lateral basis, the signals employed in the single artificial macropore experiments should exist in only the region between the electrodes. Only the 20 L source should have significant potential for higher lateral spread. For all three sources, the location of the macropore was the peak lateral signal (fig. 5). Data from 1D lateral lines (fig. 5) come from single horizon of data in larger dataset (fig. 3). The lateral effects with the presence of the metal rod are displayed as a change in conductance as a distance away from the metal rod's location for the spacings to each side of the rod location. The width of the lateral effects gets larger with increased spacings, but the signal was contained to the data blocks in the adjacent stake spacing location from the location of the artificial macropore (fig. 5). The location was detected properly, with a width of three times the actual location for the macropore.

MULTIPLE MACROPORES SATURATED VS. UNSATURATED

The experiment to test multiple macropores allows a comparison between three artificial macropores, two that experience only precipitation and one that experiences a saturated condition after precipitation using the macropore infiltrometer. The results for the experiment on a vertical basis showed a similar change with conductivity in relation to depth as the single macropore resolution tests. The peak of conductance changes sharply at the 0.5-m depth base of the macropores. As expected, the saturated macropore exhibited a larger change conductance than precipitation alone, but not significantly (fig. 6). The bulk conductivity changes between the three macropores was stronger than the single macropore experiment as more water was applied in the experiment. All three macropores appeared to have activated during the unsaturated experiment with the sprinkler wetting source.

The differences in these experiments compared to the single macropore experiments was that the peak was not aligned as nicely with the location of the macropore and was potentially in the adjacent spacing area from the location of the macropore. As the wetting was not applied to the macropore itself, this was not unexpected. The width of the saturated experiment using the macropore infiltrometer was also broader than for the single macropore experiments. This was also not unexpected as the subsurface had a significantly higher quantity of water applied during this experiment.

COARSE SOIL VS. FINE SOIL

The results for the coarse soil are similar to the fine soil with the unsaturated profiles not qualitatively different in trends relative to the saturated experiments (fig. 7). At both sites, the saturated experiment generated a slightly higher change in bulk conductivity near the top of the profile, but the shape of the resulting signal was otherwise roughly identical. The coarse site had overall larger changes in bulk conductivity based on a different media. No apparent changes in macropore activation were detected between the two sites.

Figure 5. Lateral effects showing all wetting sources for the single artificial macropore experiment at a TERI image horizontal profile. Gray line represents the metal rod signal, the orange line is the 2 L of water signal and the blue line is the signal generated by 20 L of water. The location of the artificial macropore laterally is indicated by the vertical gray line. The location of the electrodes for the 0.4-m spacing relative to the datapoints is provided as blue crosses. Instrumental noise of 0.5% indicated as well as 2.5% site noise level generated by temperature and soil moisture changes over time in experimental plot.

Figure 6. Lateral changes in bulk electrical conductivity in a three artificial macropore experiment (macropore locations as vertical lines) that had artificial precipitation applied first to produce an unsaturated upper boundary condition (orange line). The center macropore was then saturated using a macropore infiltrometer during the next TERI experiment (blue line).

Both sites had active macropore flow in both the macropore infiltrometer saturated condition and the high artificial precipitation wetting condition.

DISCUSSION

Utilizing small time differences in an artificially controlled macropore with artificial precipitation, low background noise levels were achieved in the TERI datasets. These noise levels were below normal variations in surficial temperature or soil moisture changes (Robinson et al., 2012). The experiments allow a measurement of the ER signal generated by a single macropore in the subsurface, which is only a signal between 1% and 2% change for a metal rod simulating a macropore filled with high salinity fluids. Under natural field conditions, this signal would be undetectable.

The experiment also allowed the data to clearly indicate that negative resistivity changes beneath the wetting signal were not due to soil moisture migration, but simply an artifact of the method. As the experiment had both low noise

and low signal, in some cases these negative resistivity changes were similar in magnitude to the wetting positive change in resistivity (figs. 4 and 7). These changes should relate to the location of positive changes in resistivity and should not be interpreted as soil moisture migration, but simply an artifact of the methods used to obtain the numerical profiles.

Several questions surrounding macropore detection using TERI were evaluated. First, can the method detect a single macropore? Second, how precisely is a macropore flow located with TERI? Finally, what does TERI indicate about the activation of macropores?

CAN TERI DETECT A SINGLE MACROPORE?

The metal rod used to simulate a macropore filled with saline fluid with no lateral flow was detectable with high resolution (low stake spacing) and low noise (figs. 3 and 5) which would not be possible in some soil settings (Moysey and Liu, 2012). The small electrode spacing was repeatable, but the approach would be difficult to use as a method to access large riparian areas except at spot locations due to the effort required. The low noise level achieved may not be repeatable as other field sites may have higher background noise (fig. 5). Additionally, if the temporal difference between surveys was before and after rain events, the longer time between imaging events would result in greater noise due to heating and vegetative effects (fig. 3) (Robinson et al., 2012; Acharya et al., 2017).

DOES TERI LOCATE MACROPORE FLOW PRECISELY?

In a normal freshwater soil environment, a fluid filled macropore would not provide as great of a resistivity contrast with media as the metal rod did. Detecting an active macropore would require detection of wetted media around the macropore for typical size macropores (fig. 5). The conductive fingering that may be generated could be near a macropore, but lateral migration of fluids would only show the rough location laterally (fig. 6). Additionally, a narrow stronger wetting front would look similar to a broader weaker zone due to the lateral spread of the TERI data. The technique would provide a reasonable estimate for the depth of the macropores if they are responsible for generating the fingering signal (fig. 4). The shape could also be produced by a change in the media other than macropores that would cause a high hydraulic conductivity pathway. Such results suggested that TERI could be a valuable tool for detecting and qualitatively indicating the presence of preferential flow in riparian buffers. This could then signal the need to consider additional methods for partitioning the infiltration into matrix and infiltration components such as those discussed by Guertault et al. (2021).

WHEN DO MACROPORES ACTIVATE?

The change in bulk conductivity generated by the artificial macropores wetted by sprinkler was only slightly weaker than the signal obtained by saturation from the macropore infiltrometer (fig. 6). Whether an unsaturated boundary was simulated with a sprinkler, or the macropore infiltrometer provided a fully saturated macropore, there was a higher change in bulk conductivity near the macropores.

Figure 7. Vertical profiles of TERI datasets at the location of artificial macropores for coarse (C) and fine sites (F). Unsaturated wetting conditions were generated with a sprinkler. A continuous flow from a macropore infiltrometer was used to generate a saturated profile.

This indicated preferential flow through macropore activation does not require complete saturation of the upper boundary conditions in these experiments (fig. 6). Artificial precipitation rates were comparable to a heavy rainfall event, so the macropores may not activate under lighter precipitation events. Preferential flow activating under unsaturated flow conditions in riparian buffers suggests macropore infiltration as a significant contributor to total infiltration across a range of storm intensities. Such results further support the need for design tools and analyses that consider preferential flow in quantifying the effectiveness of riparian buffers. Additional research into macropore activation mechanism would be required, but the TERI approach may be useful in evaluating alternative conceptual models.

FUTURE RESEARCH

The results suggest TERI can be useful in evaluating macropore flow as a method to detect areas that have changed electrical properties due to changes in soil moisture. However, this detection as a spatial characterization is insufficient to evaluate macropore flow as compared to soil fractures or grain size heterogeneity in the soil matrix. If the subsurface matrix properties are well understood, the TERI data can be used to illustrate where anomalous wetted areas are distributed (fig. 6). The results suggest that mapping macropores with the method may be better achieved by evaluating the rate of changes of electrical properties at a single location as macropore changes should occur more quickly than those due to matrix heterogeneity.

CONCLUSIONS

Artificial macropores were detected using TERI in a field environment in a fine-grained soil as an increase in bulk conductance finger in the subsurface. In a low noise environment, a 6 mm metal rod, simulating a saline fluid filled macropore, was detected using 0.4 and 0.8 m electrode spacings. The detection provided a good depth control and lateral location of the macropore, but a broader lateral extent. When a perimeter around the macropore was wetted with 2 or 20 L of water, a similar result was obtained with progressively stronger signals.

Experiments in fine and coarse-grained soils at two sites in Oklahoma and North Carolina, USA demonstrated that artificial macropores can activate under both unsaturated and saturated surface conditions. The unsaturated conditions were generated by sprinklers simulating a large rain event, and the saturated conditions were generated by a macropore infiltrometer consisting of a bucket with a macropore size hole used to feed water directly into an artificial macropore. While the magnitude of the change in bulk conductance was different in the different sites, the response measured by the TERI datasets was similar between the two sites.

ACKNOWLEDGEMENTS

Thanks to Jordon Massey for assistance in the field and valuable discussions on developing the field experiments. Thanks also to three anonymous reviewers who significantly improved the manuscript. This work was funded by USDA

National Institute of Food and Agriculture (NIFA) Project 2016-67019-26855. Dr. Halihan has a managed conflict of interest with regards to resistivity developments.

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