Applicability of soil moisture sensors for monitoring water dynamics in rock: A field test in weathered limestone

Pedro A. M. Leite | Bradford P. Wilcox | Kevin J. McInnes | John W. Walker

1 Dep. of Ecology and Conservation Biology, Texas A&M Univ., College Station, TX 77843, USA
2 Dep. of Soil and Crop Sciences, Texas A&M Univ., College Station, TX 77843, USA
3 Texas A&M AgriLife Research and Extension Center, San Angelo, TX 76901, USA

Correspondence
Pedro A. M. Leite, Dep. of Ecology and Conservation Biology, Texas A&M Univ., College Station, TX 77843, USA.
Email: pedroleite@tamu.edu

Abstract
Rock moisture in the vadose zone, while recognized as important, is rarely monitored—in part because adequate instrumentation and installation techniques are lacking. The objectives of this work were (a) to test the applicability of a commercially available capacitance soil moisture sensor (EC-5, METER Group) for continuously monitoring the water content of weathered limestone; and (b) to contrast the water dynamics of rock matrix with that of rock fractures. At a site in the Edwards Plateau, Texas, we developed a protocol for installing sensors in limestone pits and tested its effectiveness in reducing erroneous readings caused by installation-induced preferential flow along pit walls. Our results show that rock moisture can be accurately measured with EC-5 sensors, provided some steps are taken to ensure the quality of the installation. These include protecting the sensors by installing them in horizontal shafts rather than on the exposed pit wall, and use of a sealant. Data gathered over 7 mo after installation showed that rock moisture increased significantly only after a 95-mm rainfall event. Because of preferential flow, fractures reached peak water content within 2–3 h after peak rainfall—a response that was one to two orders of magnitude faster than in rock matrix. Limestone stored 40–70% of the water after the 95-mm event, and its water content decreased significantly during summer months. Overall, our results attest to the importance of continuously measuring rock moisture in regions with shallow soils, where it serves as a critical reservoir for vegetation.

1 INTRODUCTION

The ability to measure volumetric water content (VWC) in the vadose zone is critical for understanding and monitoring key hydrological processes such as evapotranspiration, contaminant flow, and groundwater recharge. Although soil water measurements are almost always a part of such studies, considerably less attention has been given to rock water content, despite its well-recognized importance for sustaining plant transpiration in regions with shallow soils (Graham et al., 1994; Schwinning, 2010). Recently, however, this factor has been gaining increasing attention. Not only have new studies revealed that rock moisture can support the transpiration of entire Mediterranean-climate forests during the dry season (Hahm et al., 2020; Rempe & Dietrich, 2018), but there is growing evidence that in semiarid karst savannas, porous limestone serves as a key water reservoir for shrubs and trees.

Abbreviations: MAE, mean absolute error; TDR, time domain reflectometry; VWC, volumetric water content.
Juniperus ashei (Moric.) Fedde], and live oak [Quercus virginiana].

For the fine (measured on cobbles 2 mm) fraction of the soil, and 31% for the coarse fraction (measured on cobbles >50 mm). Previous excavations show that the weathered limestone (Cr horizon) starts at 0.1–0.4 m deep and can extend beyond 2.5 m. In some locations, the rock is friable and highly weathered, and roots and fractures can be found. In other locations, however, the limestone is much harder and has no visible roots or fractures, indicating less weathering. Such high variability in weathering patterns is typical of karst formations. The average porosity of the limestone, based on analysis of samples, is 36 ± 7%. See the supplemental material for more detailed information on the soil and rock properties of this site—including texture, bulk density, VWC at saturation, and total porosity—and the methods used to measure them.

Core Ideas

- EC-5 sensors proved to be successful for monitoring the water content of weathered limestone.
- Installation-induced errors can be avoided by following strict installation protocols.
- The amount of water infiltrating the weathered rock after large storms can be substantial.
- Rock moisture increases rapidly after storms as a result of preferential flow through fractures.
- Rock moisture was more depleted during the summer than during the fall dry season.

2 MATERIALS AND METHODS

2.1 Study site

We performed our study at the Texas A&M Research Station near Sonora, TX. The station is located in the southwestern portion of the Edwards Plateau, a large karstic geographic region that is home to the Edwards Aquifer, one of the most productive artesian aquifers in the world and the main source of water for millions of people, including the inhabitants of the city of San Antonio. Mean annual precipitation at our site is around 560 mm, with 70% of the rainfall occurring between May and October. Mean annual temperature is 18 °C, with January being the coldest month with a mean of 8 °C and July being the warmest with a mean of 28 °C (Western Regional Climate Center). The dominant woody plants are the evergreens Ashe juniper (Juniperus ashei J. Buchholz), redberry juniper (Juniperus pinchotii Sudw.), algerita [Mahonia trifoliolata (Moric.) Fedde], and live oak [Quercus virginiana Mill. var. fusiformis (Small) Sarg.].

Our site is underlain by the Buda formation, which consists of 15–30 m of Upper Cretaceous fine-grained, bioclastic, and highly porous limestone. The site has gentle slopes of 1–3%, and the soils are very shallow (0.1–0.4 m), clayey-skeletal, smectitic, thermic Petrocalcic Calciustolls (Soil Survey Staff, 2016). The mean particle size composition of the soils is 38 ± 5% clay, 47 ± 6% silt, and 15 ± 3% sand. The soils are nonsaline (electrical conductivity < 1 dS m⁻¹), and approximately one-fifth of their volume consists of limestone rocks, mostly cobble size. Mean porosity is 54 ± 7% for the fine (<2 mm) fraction of the soil, and 31 ± 6% for the coarse fraction (measured on cobbles >50 mm). Previous laboratory studies have tested the applicability of different sensors for measuring VWC of rock samples (Caputo et al., 2013; Hokett et al., 1992; Sakaki & Rajaram, 2006; Sakaki et al., 1998; Schneebeili et al., 1995), attempts to continuously monitor VWC of rock under field conditions are still rare (Salve, 2011; Salve & Rempe, 2013; Sass, 2005).

Particularly lacking are studies of rock moisture changes in karst regions with shallow soils overlying porous limestone. These regions can be important sources of groundwater recharge. Continuous measurement of VWC of weathered limestone in the vadose zone can help us better understand how changes in vegetation and land use affect the water budget in karst regions with shallow soils. However, a major impediment is that the commercially available sensors that could be used for this purpose were developed for measuring moisture in soils; their installation in rock medium is logistically challenging and requires adaptations of the standard installation protocols.

The main objective of our study was to test the applicability of a commercially available soil moisture sensor for continuous monitoring of limestone VWC under field conditions. We developed a protocol for installation of soil moisture sensors in limestone pits, tested the efficacy of this method for reducing erroneous readings caused by preferential flow along pit walls, and performed medium-specific calibrations. Then, over a 7-mo period, we tracked and compared changes in VWC of soil, limestone matrix, and fractures in limestone.
2.2 | Sensor installation protocol

In April 2020, using a backhoe, we excavated four pits. Their depths varied between 1 and 1.5 m, and they were all approximately 2 m long × 0.6 m wide. We removed the soil and rock material carefully and in layers corresponding as much as possible to the different horizons, so that we could backfill the pits in the same order.

In preliminary trials, it proved to be extremely difficult to install time domain reflectometry (TDR) sensors (TDR-310H, Acclima), with their three 10-cm-long prongs, in the limestone-dominated matrix without unacceptable levels of disturbance or bending of the prongs. Therefore, we opted to use shorter (5-cm-long) soil moisture sensors (EC-5, METER Group). Although we are unaware of other studies using these sensors in weathered rock, they have been tested in a wide variety of soils with successful results (Hao et al., 2019; Kukowski et al., 2013; Magliano et al., 2015; Niemeyer et al., 2017; Zou et al., 2014). Further, they have not only proved to be as accurate as TDR sensors (Czarnomski et al., 2005; Sakaki et al., 2008) but have the advantage of being less expensive. The downsides are that they have a relatively small volume of influence (0.2 L) and are highly sensitive to air gaps between the sensor and the material. To compare the accuracy of the EC-5 sensors with that of the TDR-310H sensors, we performed our own laboratory calibrations (described below in Section 3.3).

A possible complication with the installation of soil moisture sensors in pits is that preferential pathways for water flow can be artificially created along the pit wall or sensor cables, which may distort VWC readings (Basara & Crawford, 2000). We expect that such preferential flow is likely in limestone pits, since repacked limestone would probably have larger air gaps and pores than intact limestone. For this reason, we carried out an initial experiment in one of the four pits to evaluate a technique for protecting the sensors from the effects of preferential flow, the success of which would enable us to design an effective installation protocol for all four pits.

For this initial experiment, we used two types of sensor installation: (a) directly on the face of the pit, at three depths (40, 60, and 80 cm), and (b) at the back of horizontal shafts cut into the pit wall at the same three depths, followed by packing of the shafts with a limestone cementing mixture and application of a spray-on sealant (the protocol is described in detail below). We carefully backfilled the pit with the limestone spoils to a depth of 30 cm, and using a backpack sprayer, we simulated rainfall by spraying 50 L of water (i.e., about 50 mm of simulated rainfall) over ~1 m² of the backfilled limestone (Figure 1). The simulation took about 20 min to complete. We then measured the VWC of the limestone for three days; the results showed changes in VWC only for the sensors installed directly on the pit wall (Figure 2). We therefore concluded that the shaft installation followed by packing with a cementing mixture and application of a sealant was effective in preventing installation-induced preferential flow from reaching the sensors. A possible drawback of this protocol is that it reduces the number of lateral flow paths to the sensor location. Nonetheless, we considered that the benefit of avoiding misleading VWC readings outweighs the potential disadvantages and implemented this protocol when installing sensors in the other three pits.

In each pit, we installed sensors at four depths: 20 cm in the soil and 40, 60, and 80 cm in the weathered limestone. The sensors installed in the limestone were placed either in fractures or directly into the limestone matrix, depending on the conditions at the selected depths and positions. The limestone of two of our pits (Pits 1 and 2) was clearly more fractured than that of Pits 3 and 4. Fractures were easily identified, as they were normally filled with roots (Figure 3a). At each depth in the limestone we drilled a horizontal shaft approximately 15 cm in diameter and 20 cm deep, at the back of which we installed the sensor (Figures 1 and 3b).

To install the sensors, we used an insertion tool—a 16-mm (5/8-inch) spade drill bit shaped to the EC-5 sensor width and thickness (Figure 3c). A pilot slit was made at the back of the horizontal shaft, by slowly hammering the insertion tool 5 cm into the limestone matrix or fracture and then carefully removing it. Because capacitance moisture sensors such as the EC-5 require good contact with the material to provide reliable VWC results (Cobos & Chambers, 2010), the pilot slit was packed with a cementing mixture (limestone powder was sieved through a 1-mm-diam. mesh, water was slowly added, and the mixture was manually blended and squeezed to a homogeneous and sticky consistency). The sensors were then pushed into the mixture in the slit (Figure 3d). After sensor installation, the horizontal shafts were backfilled...
and tightly packed with the limestone cementing mixture (Figure 2e), then left to dry and harden for 48 h. To install the sensors at the 20-cm depth (in the soil), we hand excavated the shafts by removing soil and rocks. We then pushed the sensors directly into the soil at the back of the shaft, purposefully avoiding proximity to rocks to ensure that most of their volume of influence consisted of soil. The shafts were then backfilled with moistened soil sieved through a 2-mm-diam. mesh. Finally, we applied a spray-on sealant (Rust-Oleum Leak Seal) over an area of approximately 1 m² covering all four shafts and allowed it to dry for 24 h (Figure 2f). Preliminary trials on limestone fragments sprayed with this sealant showed that the sealant is not absorbed by the rock (probably owing to its high viscosity), and therefore it does not affect the physical properties of the limestone surrounding the sensors.

2.3 | Sensor calibration

According to manufacturer specifications, the internal calibration of the EC-5 sensors should give soil moisture results with an accuracy of ±3 cm³ cm⁻³ for most mineral soils having solution electrical conductivities <8 dS m⁻¹. As with most (if not all) soil moisture sensors, a medium-specific calibration of the sensors was expected to significantly improve the accuracy of the VWC readings. Bulk density, for example, is known to affect the VWC readings of capacitance sensors, and the bulk density of limestone is normally higher than that of most soils. For this reason, we performed our own medium-specific calibration for both the soil and the limestone at our site, using the bucket calibration method (Starr & Paltineanu, 2002).
From each of our pits we took a 2-kg sample of soil and a 2-kg sample of limestone (crushed and sieved through a 1-mm-diam. mesh). We combined and thoroughly mixed the four soil samples and packed 6 kg of the mixture into a 5-L bucket, to near field bulk density. We then followed the same procedure with the four limestone samples. Next, we inserted five EC-5 sensors and five TDR-310H sensors, one at a time, into each of the two buckets, pushing them tightly into the packed samples, and recorded the VWC readings. To obtain the actual VWCs of the soil and limestone mixtures, we did gravimetric analyses using small cylindrical cores (70 cm³) taken from the surface to the 5-cm depth. We repeated these procedures at five different water contents, achieved by transferring the packed material into a 20-L bucket and adding known volumes of water to the sample, thoroughly mixing each time.

Medium-specific calibration equations were generated by simple linear regressions between the actual VWCs of the samples (obtained gravimetrically from the small cores) and the sensors’ VWC outputs (factory calibration). To compare the accuracy of these medium-specific calibration equations with that of the factory calibrations, we calculated the mean absolute error (MAE) between (a) the VWCs based on factory calibrations and the actual VWC; and (b) the VWCs based on medium-specific calibrations and the actual VWC.

To determine whether our medium-specific calibrations significantly improved the accuracy of VWC estimations, we used paired t tests to detect differences between the MAE of the factory and medium-specific calibrations.

### 2.4 Field measurements and data analysis

The VWC values measured by the sensors in the four pits were recorded every 10 min with HOBO U30 dataloggers, and rainfall was continuously monitored with a RG3 HOBO tipping-bucket rain gauge (Onset).

Cumulative changes in water content were estimated for the upper 90 cm of fill in each pit. We assumed that the VWC values measured by each sensor installed in limestone represented the VWC of a 20-cm layer (from 10 cm above to 10 cm below the sensor). For the sensors installed in soil, we assumed the measured values to represent the VWC of the entire soil profile (from 0 to 30 cm). Since the sensors were installed at the 20-cm depth, this assumption could lead to underestimates of storage at shallower depths, especially after small rainfall events. For this reason, we restricted our analysis to a single large event (9–10 September), in the wake of which all sensors showed steep increases in VWC and the entire soil profile likely reached field capacity.

As in other subtropical regions, heat fluxes and evapotranspiration rates in the Edwards Plateau are higher during the summer than during the fall (Heilman et al., 2009). In addition, the depth of water uptake by woody plants in this region is known to vary across seasons (Elkington et al., 2014). For these reasons, we expected to see differences in soil and rock moisture decline between the summer and fall months. To evaluate this drying trend, we used two 32-d periods: one in midsummer (between 12 July and 14 August), during which total precipitation was only 2.7 mm, and one completely rainless period in early fall (between 22 September and 24 October). For each 32-d period, we calculated ΔVWC as the difference between VWC at the end and VWC at the beginning.

To contrast the rates of change in VWC among the various sensor locations (soil, limestone fracture, and limestone matrix) in response to the 9–10 September storms, we used the following parameters: (a) response lag, defined as the time between the start of rainfall and the first increase in VWC; (b) lag to peak, defined as the time between peak rainfall and peak response; and (c) peak response, defined as the difference between maximum VWC and VWC during peak rainfall. These parameters, represented schematically in Figure 4, have been used in other studies to contrast the hydrological responses measured by TDR sensors installed in rock with different backfills (Salve & Rempe, 2013).

### 3 RESULTS AND DISCUSSION

#### 3.1 Protecting sensors from preferential flow

The sensors installed in shafts cut into the limestone pit wall, which was then coated with sealant, showed no changes in VWC throughout the rainfall simulation test. Conversely, the sensors installed directly in the exposed pit wall and without sealant did show changes: the sensor at 40 cm recorded a sharp increase in VWC soon after water application, whereas those at 60 and 80 cm showed small and gradual increments in VWC (see Figure 2). Because water was applied only to the limestone backfill, which was not directly above these sensors (Figure 1), we can conclude that (a) the rapid increase in VWC observed immediately after water application for the sensor installed directly in the exposed pit wall at 40 cm reflected fast, installation-induced preferential flow; and (b) in contrast, the small and gradual increases observed for the sensors at 60 and 80 cm reflected slower matrix flow.

Even though our experiment did not attempt to replicate natural field conditions, as the rainfall simulation was applied directly on top of the limestone backfill and covered only a small area, the results still show that, particularly with high rainfall amounts, sensor installation can lead to artificial preferential flow—often regarded as a potential...
source of VWC errors (Basara & Crawford, 2000; Cooper, 2016; Doležal et al., 2012; Dorigo et al., 2013; Junqueira et al., 2017). For this reason, it is important to ensure careful installation of the sensors, using methods such as those adopted in our study, which eliminated misleading VWC readings. To date, however, few studies have documented the occurrence of installation-induced preferential flow or developed methods to avoid its potentially serious effects. One exception is the study of Basara and Crawford (2000), who found that installation-induced preferential flow along sensor cables and trench walls was leading to unrealistic VWC readings. They were able to eliminate the problem simply by installing the sensors in horizontal shafts cut perpendicular to the trench face and compacting the backfill to its original density. Because backfilled material may not be easily compacted to its original density in all circumstances, additional measures are advisable (e.g., application of a sealant spray, as done in our study). More studies are needed to clarify how common artificially induced preferential flow is when sensors are installed in pit walls (in both soil and rock), and what measures are effective in avoiding this artifact.

### 3.2 Calibration of sensors

Our medium-specific calibrations for both limestone and soil had very high coefficients of determination ($R^2 \geq 0.98$; Figure 5). For the VWC of limestone, the factory calibration MAE for the EC-5 sensors was 0.023 cm$^3$ cm$^{-3}$ vs. 0.015 cm$^3$ cm$^{-3}$ for our medium-specific calibration; and the factory calibration MAE for the TDR-310H sensors was 0.013 cm$^3$ cm$^{-3}$, vs. 0.01 cm$^3$ cm$^{-3}$ for our medium-specific calibration. For the VWC of soil, the factory calibration MAE for the EC-5 sensors was 0.024 cm$^3$ cm$^{-3}$, vs. 0.014 cm$^3$ cm$^{-3}$ for our medium-specific calibration; and the factory calibration MAE for the TDR-310H sensors was 0.052 cm$^3$ cm$^{-3}$, vs. 0.016 cm$^3$ cm$^{-3}$ for our medium-specific calibration. In all cases, the medium-specific calibrations statistically improved the accuracy of VWC estimations at the .05 level of significance.

Our medium-specific calibrations improved the accuracy of VWC readings obtained with the EC-5, confirming the findings of other researchers who did their own medium-specific calibrations and were able to improve sensor accuracy—not only of EC-5 sensors (Francesca et al., 2010; Wu et al., 2014) but other similar sensors (Domínguez-Niño et al., 2019; Varble & Chávez, 2011). For our limestone medium, the factory calibration of the EC-5 tended to give overestimates at lower water contents and slight underestimates at higher water contents. For soil, it provided accurate estimates at the lower VWC ranges but underestimated water content when conditions were wetter. Still, the overall factory calibration errors (±0.023 cm$^3$ cm$^{-3}$ for crushed limestone and ±0.024 cm$^3$ cm$^{-3}$ for soil) were within the ±0.03 cm$^3$ cm$^{-3}$ error margin advertised by the sensor manufacturer for most mineral soils. Therefore, for most applications that do not require greater accuracy, the factory calibration would suffice.

In our study, the laboratory calibration that most improved the accuracy of the VWC readings was the one performed for the TDR-310H in the soil medium (Figure 5). At water contents below 0.2 cm$^3$ cm$^{-3}$, the factory calibration of these sensors underestimated the moisture content of our soils by approximately 60%. Such a considerable level of error was somewhat surprising, since the factory calibration for these sensors gave very accurate readings for the crushed limestone medium. Its inaccuracy for the soil medium might be attributable to the high organic matter content, ranging between 6 and 17% (Knight et al., 1984). Other work has shown that the use of mineral soil calibrations for TDR measurements in soils with high organic matter can result in VWC underestimates of up to 60% (Schaap et al., 1997).
3.3 | Field measurements

Significant increases in VWC were recorded by all sensors only after two heavy storms on 9–10 September, considered to be a single event because they occurred less than 24 h apart (Figure 6). Total precipitation during this event was 95 mm, which represents 41% of the total 234 mm measured during our 7-mo study. Events of this magnitude have a return period of 2–5 yr in this region (Cleveland et al., 2015).

3.3.1 | Transient water storage

Changes in transient water storage (averaged for the 90-cm depth in all four pits) during and after the 9–10 September storms were consistent with cumulative precipitation over the period (Figure 7). Measurements taken 24 h after the storm showed that mean storage at this depth had increased by 78 mm, but there was significant variability among the pits: the more highly fractured Pits 1 and 2 saw greater increases (93 and 102 mm, respectively) than Pits 3 and 4 (76 and 43 mm, respectively). Additionally, for Pits 1 and 2, water stored in the weathered limestone accounted for 60 and 70% of the total, respectively, compared with 45 and 40% for Pits 3 and 4, respectively.

Because VWC is highest in fractures, water storage at peak response for Pits 1 and 2 was two to three times higher than cumulative precipitation. Such a discrepancy could be explained by additional water inputs to those pits in the form of runoff infiltrating through fractures. Conversely, cumulative water storage in Pits 3 and 4 was lower than precipitation, which suggests that they could have acted as runoff sources. However, storage estimations based on VWC measured by sensors having a small volume of influence (0.2 L in the case of EC-5 sensors) must be interpreted with caution when applied to highly heterogeneous media such as our weathered limestone. Extrapolating VWC from a relatively small area such as a fracture—especially during peak response—to the whole limestone layer might lead to overestimations of water storage. Additionally, the fact that a sensor installed in a fracture at 80 cm deep recorded fast and steep peak responses (see below) suggests that, in some locations, water can infiltrate deeper than 80 cm; for this reason, sensors may need to be installed at greater depths to capture the full root zone.
### Table 1

| Location       | Depth | N sensors | ΔVWC summer cm⁻³ | ΔVWC fall cm⁻³ | Response lag h | Lag to peak h | Peak response cm³ cm⁻³ |
|----------------|-------|-----------|-------------------|----------------|----------------|---------------|------------------------|
| Soil           | 20    | 4         | -0.03 ± 0.01      | -0.06 ± 0.02   | 2.3 ± 0.9      | 2.8 ± 1.4     | 0.1 ± 0.06              |
| Limestone (fracture) | 40    | 3         | -0.03 ± 0.02      | -0.04 ± 0.03   | 3.6 ± 2.5      | 6.8 ± 6.1     | 0.1 ± 0.04              |
|                | 60    | 2         | -0.03 ± 0.01      | -0.02 ± 0.004  | 2.8 ± 0.4      | 2.3 ± 0.5     | 0.35 ± 0.09             |
|                | 80    | 1         | -0.02             | -0.03          | 2.1            | 1.7           | 0.31                   |
| Limestone (matrix) | 40    | 1         | -0.04             | -0.01          | 24             | 226           | 0.09                   |
|                | 60    | 2         | -0.03 ± 0.01      | +0.01 ± 0.02   | 104 ± 86       | 490 ± 360     | 0.05 ± 0.004            |
|                | 80    | 3         | -0.02 ± 0.01      | +0.01 ± 0.01   | 184 ± 177      | 560 ± 519     | 0.03 ± 0.02             |

Note: The parameters ΔVWC summer and ΔVWC fall represent the changes in VWC during two 32-d dry periods, one in the summer and one in the fall. Negative and positive values indicate loss and gain of water, respectively.

### Figure 6

The top graph shows total precipitation (measured hourly) and cumulative precipitation for the 7-mo duration of the study. The blue areas represent two 32-d dry periods, one in midsummer and one in early fall. The bottom graphs show average hourly changes in volumetric water content (VWC) for the four pits, measured with EC-5 sensors installed at the 20-cm depth (in soil) and at depths of 40, 60, and 80 cm (in fractures or matrix of weathered limestone).

### Figure 3.3.2 Drying trends during periods of scant rainfall

During the summer, ΔVWC was similar at all depths and locations, ranging between 0.02 and 0.04 cm³ cm⁻³. In contrast, during the fall there were clear differences in drying trends between soil, limestone fractures, and limestone matrix. In both soils and fractures, VWC declined by 0.06 and by 0.03 cm³ cm⁻³ (average for all depths), respectively; whereas in limestone matrix, VWC increased slightly (by 0.01 cm³ cm⁻³) except for at the 40-cm depth, which showed a decrease of 0.01 cm³ cm⁻³ (Table 1).

A possible interpretation of these results is that in the fall, when VWC was generally higher, more moisture was drawn from the soil layers by vegetation than from the rock (possibly because water potentials are less negative for soil than for rock at the same VWC). Conversely, in the summer, when soil moisture is depleted, rock moisture becomes an important source for sustaining minimum vegetation requirements (Schwinning, 2020). After the storms of 9–10 September, significantly more water reached greater depths than after the rainfall events preceding the summer dry period. Most of the water that infiltrated through fractures was likely slowly absorbed by the matrix, which would explain the gradual increase in matrix moisture concomitant with the decrease in fracture moisture. In addition, some of the water from the fractures might have been transpired by vegetation. Because our site is located on gently sloping terrain with no springs or stream channels, and because groundwater recharge in the region happens mainly through transmission losses in stream channels (Green et al., 2014), we believe that little to no water moved past the root zone to become spring flow or groundwater recharge.

### Figure 3.3.3 Responses to storms

Response-lag and lag-to-peak times in limestone fractures were similar to those in soil. Irrespective of depth, all sensors installed in fractures showed steep increases in VWC within a few hours after the 9–10 September storm began (Figure 8; Table 1). Interestingly, in some instances, VWC in fractures started to increase even before the corresponding increases in the layers above them (e.g., the fracture at the 80-cm depth in Pit 2). This is strong evidence of preferential flow through these fractures and shows that (a) soil does not need to reach
Our results agree with the findings of the study by Dasgupta et al. (2006), carried out in the Glen Rose limestone formation in the contributing zone of the Edwards Aquifer near San Antonio, TX. After high-intensity rainfall simulations over a large plot, they monitored water outflow at a downslope trench and found that water seepage from some fractures happened within 3–5 h of the onset of rainfall, and that response times were independent of antecedent moisture conditions. They also found that changes in VWC, recorded with TDR sensors installed in karst features filled with soil, were much slower (23–30 h). On the basis of these results and the use of dye tracers, they concluded that some fractures were connected to the surface through the roots of woody plants (especially juniper), which created preferential flow channels through which water could quickly infiltrate. In our study, roots were always present in fractures (Figure 3a). The intense 9–10 September storms probably generated ponding, which built positive pressures and triggered rapid infiltration through fractures and their associated root channels, which explains the fast and steep VWC increases observed.

It was surprising that deeper fractures (at 60 and 80 cm) saw faster and steeper increases in VWC than the shallow (40-cm-deep) fractures, since fast responses should have also happened in the shallower fractures that are connected to those at greater depths. The explanation could be that preferential flow happens only in a small portion of the shallow fractures. We observed during sensor installation that the limestone at 40 cm was more fractured and friable than that at greater depths, suggesting that the matrix surrounding the shallower sensors might have relatively high hydraulic conductivity, which can prevent the onset of preferential flow (Hendrickx & Flury, 2001). It is also possible that those fractures were filled with soil material, which can slow down field capacity for preferential flow to take place, and (b) preferential flow paths in the soil must be directly connected to fractures.
water flow (Dasgupta et al., 2006). More detailed observations are needed to evaluate how widespread this pattern is. Future studies would benefit from monitoring a larger number of fractures and/or using other techniques, such as tracers.

Changes in VWC in the limestone matrix were much slower than those measured in the fractures. Lag-to-peak and peak responses were one to two orders of magnitude higher than in fractures, such that the first increases in rock moisture sometimes appeared only after several weeks. The upper layers of the limestone matrix tended to respond faster than lower layers. This type of response is typical of uniform flow (i.e., wetting fronts parallel to the surface; Hendrickx & Flury, 2001). One exception, however, was recorded by the sensor installed at the 80-cm depth in Pit 1, which responded as fast as sensors installed in fractures. No visible fractures had been noted when the sensor was installed, but an unseen fracture may have been present, explaining the unusually fast response in limestone matrix.

Although we did not establish a parameter to quantify the drainage responses immediately after the storm, it is clear from Figure 8 that when peak moisture was reached quickly, drainage was also fast. For fractures at 60 and 80 cm, for example, stable moisture contents were reached less than 12 h after peak response. At the same time, drainage from these depths seems to have occurred in two stages: an initial steep decrease in soil moisture, with most of the water draining within 2–3 h, followed by a slower decrease over the next several hours.

Peak response was highest (0.35 and 0.31 cm$^3$ cm$^{-3}$, respectively) for the fractures at 60 and 80 cm and lowest (0.05 and 0.03 cm$^3$ cm$^{-3}$, respectively) at the same depths in limestone matrix. At the 40-cm depth, however, the peak responses of limestone (both fractures and matrix) were similar to that of soil (approximately 0.1 cm$^3$ cm$^{-3}$). The higher peak responses of deeper fractures is probably also due to preferential flow, which carried large volumes of water to those depths. It is likely that during peak response, not only the fractures but also the pores in the adjacent matrix were filled with water, which in addition would explain why fractures at the 60- and 80-cm depths drained in two stages: the faster initial stage reflecting downward gravity flow, and the slower second stage reflecting matrix flow.

One of the few other studies that have used soil moisture sensors to investigate differences in VWC dynamics between rock matrix and rock fractures is that by Salve and Rempe (2013), carried out on mudstone and sandstone rocks in northern California. What they found for mudstone agrees with our results for limestone, whereas their findings for sandstone contrast with ours. For mudstone, they found that fractures consistently showed higher VWC and also dried up faster than rock matrix; for sandstone, VWC within fractures was consistently lower than in rock matrix, although wetting and drying trends were similar for the two. A possible explanation for the different hydraulic responses in sandstone than in other rock types could be the lack of preferential flow in sandstone fractures due to the high hydraulic conductivity of its matrix (Boving & Grathwohl, 2001; Hendrickx & Flury, 2001). A more in-depth analysis of the possible mechanisms involved in the hydraulic dynamics of fractures and matrix of different types of rock is beyond the scope of this paper. Nonetheless, our findings—like those of Salve and Rempe (2013)—highlight the importance of continuously monitoring rock VWC in order to better understand hydrological processes in the vadose zone of different geological settings. In particular, our work demonstrates that, for weathered rocks such as the Buda limestone in the Edwards Plateau, such monitoring can be effectively carried out through the use of reliable and relatively affordable soil moisture sensors.

## 4 CONCLUSIONS

With the growing need for methods for continuous monitoring of rock moisture, not only must new techniques and instrumentation be developed, but also some adaptations can be made to existing soil moisture sensors and conventional installation methods. Our study shows that installation of soil moisture sensors in pits is a viable strategy for measuring the VWC of weathered limestone, provided some key measures are taken to ensure the reliability and accuracy of the measurements. These include installing the sensors inside horizontal shafts rather than directly into the pit face, and the use of a sealant. We show that these measures are effective in protecting the sensors from installation-induced preferential flow along pit walls. We also found that while the EC-5 sensor’s factory calibration is appropriate for use on weathered limestone, medium-specific calibrations can significantly improve the sensor’s accuracy.

By analyzing changes in rock VWC over a 7-mo period after installation of sensors in four pits, we found that after a large storm, sensors installed in fractures showed faster and steeper increases in VWC than sensors installed in the rock matrix. This difference reflects two well-known water flow domains: matrix flow and preferential flow paths. Increases in VWC after the storm were greater in pits where fractures were more abundant, with rock moisture representing up to 70% of the transient water storage. In addition, we observed faster declines in rock moisture during summer months than during a fall dry period—likely related to seasonal variations in water demand by vegetation and in depth of water uptake. Overall, our results illustrate the importance of continuously monitoring rock moisture to improve our understanding of key ecohydrological processes in the vadose zone. Furthermore, we demonstrate that monitoring can be effectively done with affordable soil moisture sensors by making appropriate modifications to conventional installation methods.
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AUTHOR CONTRIBUTIONS

Pedro A. M. Leite: Conceptualization, Formal analysis, Investigation, Methodology, Writing-original draft. Bradford P. Wilcox: Conceptualization, Funding acquisition, Project administration, Supervision, Writing-review & editing. Kevin J. McInnes: Conceptualization, Funding acquisition, Methodology, Writing-review & editing. John W. Walker: Funding acquisition, Project administration, Resources, Writing-review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

Pedro A. M. Leite https://orcid.org/0000-0003-3337-6031
Bradford P. Wilcox https://orcid.org/0000-0002-3903-9098

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