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CONTINUOUS SOIL-MOISTURE MEASUREMENTS TO ASSESS FRACTURE FLOW IN INSCRIPTION ROCK AT EL MORRO NATIONAL MONUMENT, NEW MEXICO: IMPLICATIONS FOR THE DETERIORATION OF INSCRIPTIONS

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Abstract—Inscription Rock, the main attraction at El Morro National Monument, is a 70-m-high sandstone monolith that documents a long history of human activity. The Atsinna Pueblo ruins sit on top of the monolith above steep cliff walls that exhibit thousands of signatures carved into the sandstone by Spanish explorers and American emigrants. One of the primary goals of the National Park Service in managing the monument is the preservation of the historic inscriptions, which are deteriorating largely due to natural weathering processes that are driven by the presence of water. The loss of inscriptions is particularly noticeable on the northeastern-most point on the cliff at El Morro, where lichen is obscuring inscriptions. The experiment described here was part of a larger hydrogeologic study with the objective of identifying water sources and mechanisms by which water comes in contact with the inscriptions.

This experiment compared fluctuations in soil moisture at the base of the cliff in different areas to soil moisture fluctuations at “control points” away from the cliff, where local precipitation that falls on the surface is most likely the only source of soil moisture. Continuous soil moisture data at depths of 10 and 30 cm were collected between April 27 and October 5, 2017. Soil moisture data for sites in close proximity of the cliff showed evidence of additional soil moisture sources in areas where the cliff face was perpendicular to the northeasterly strike of the primary joint system, providing evidence of water percolating relatively quickly through these fractures. Water that is stored in these fractures that are close to the wall surface can potentially move slowly through the sandstone matrix, mainly driven by capillary action and a water potential gradient resulting from the evaporation of water that reaches the rock surface. We hypothesize that this process is occurring on the north side of Inscription Rock, where lichen growth is greatly impacting inscriptions.

INTRODUCTION

El Morro National Monument is located in northwestern New Mexico approximately 40 mi southwest of Grants and south of the Zuni Mountains (Fig 1). This national monument features the cliffs of El Morro, which served as a prominent landmark and water source (the historic pool at the base of the cliff) for Puebloan people, Spanish explorers and American settlers for hundreds of years. Inscription Rock, a 70-m-high sandstone monolith (composed of Jurassic Zuni Sandstone; Fig. 2), documents a long history of human activity, with the Atsinna Pueblo ruins on the cliff top, and rock art that includes thousands of symbols and signatures carved into the cliff walls by Native Americans, Spanish explorers and American emigrants. One of the primary management goals of El Morro National Monument, which was established in 1906, is the preservation of these historic inscriptions, which are deteriorating due to natural and anthropogenic processes. The loss of inscriptions is particularly noticeable on the north side of Inscription Rock in the vicinity of North Point, the northeastern-most point on the cliff at El Morro, where lichen is obscuring inscriptions (Burris, 2007). Much research has been conducted to understand the natural erosional processes that contribute to the deterioration of these inscriptions in order to identify possible methods to mitigate the eventual loss of the inscriptions. Important weathering processes that contribute

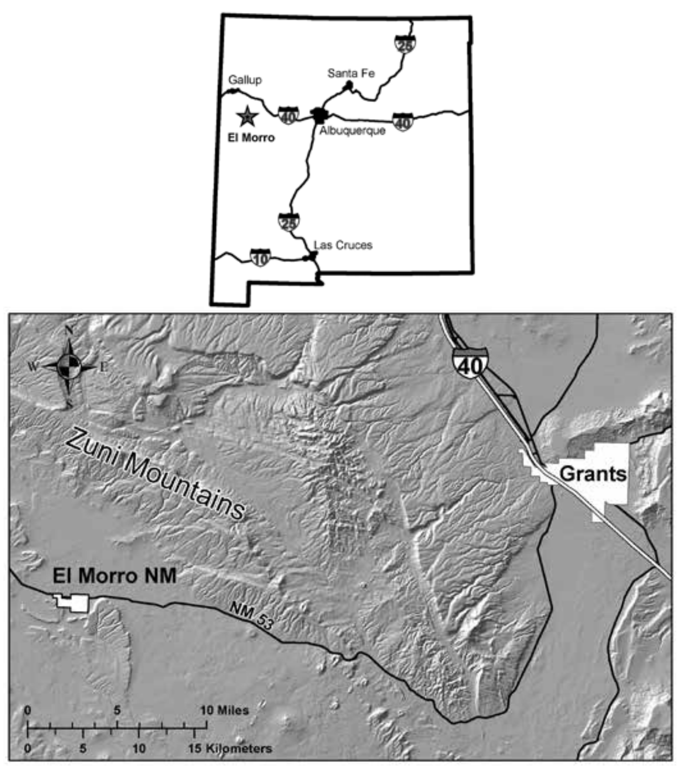

FIGURE 1. Index map showing the location of El Morro National Monument, New Mexico.

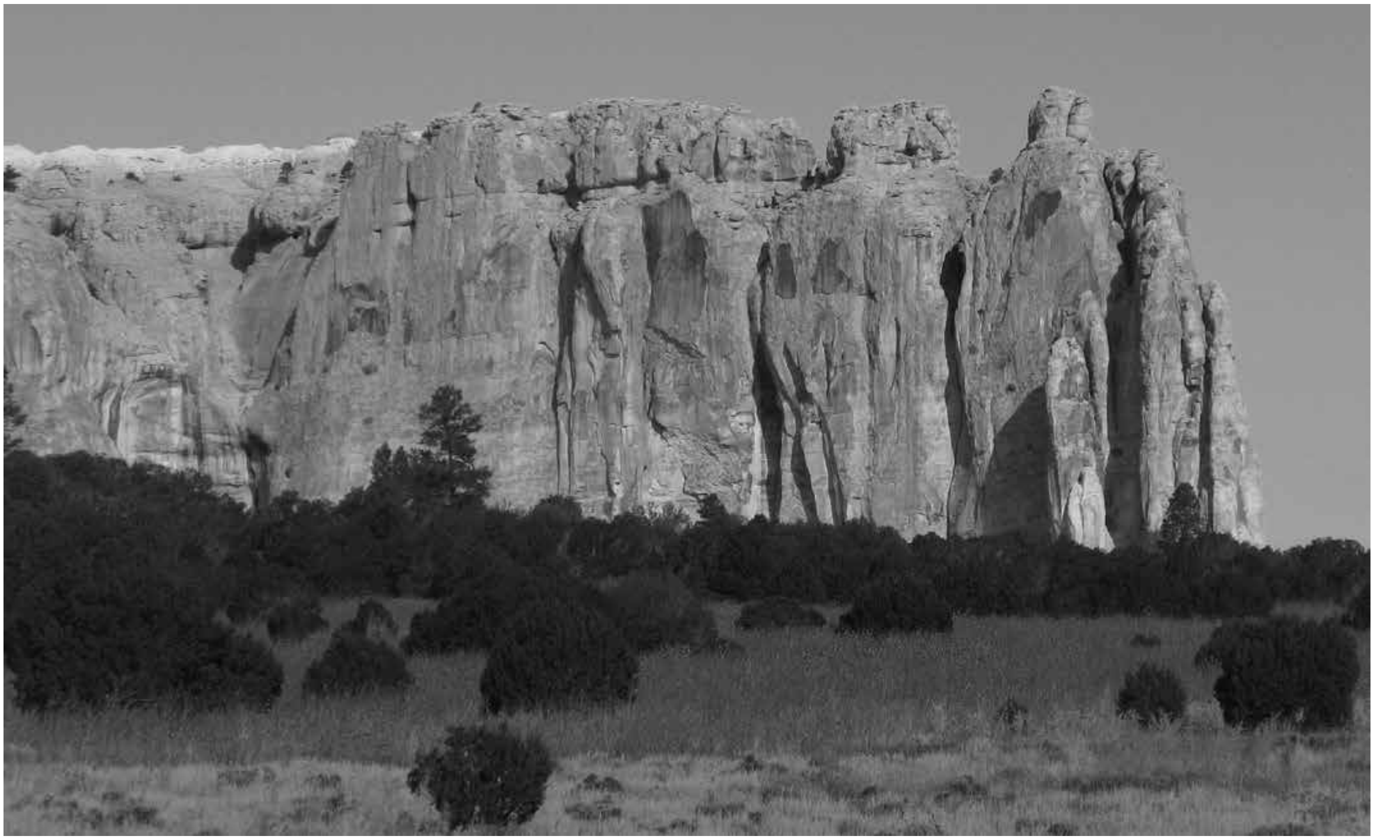

FIGURE 2. Photograph of Inscription Rock at El Morro National Monument in New Mexico. The part of the Zuni Sandstone cliff at the far right is called North Point. The view is from the road to the visitor's center, looking north.

to the deterioration of the inscriptions include (Padgett, 1992; Cross, 1996; Pranger, 2002):

- Granular disintegration — the separation of individual grains or clumps of grains by physical removal due to pelting rain or water flow over the cliff face or by freezing and thawing of water in pores and in fractures;
- Rockfall — the detachment of coherent blocks;
- Spalling — the shedding of small, relatively thin flakes of rock by alternating wetting and drying or from capillary rise from wet soil at the base of a cliff;
- Biological factors — insect borings or lichen growth.

The presence of water drives many of these weathering processes. Research focused on the local hydrogeology has made progress toward the identification of surface and subsurface water sources that contribute to weathering processes (Padgett, 1992; Cross, 1996; Pranger, 2002; Van Dam and Hendrickx, 2007). However, there are significant questions about the hydrogeologic system that need to be answered before mitigation techniques to help preserve the inscriptions can be assessed. A recent hydrogeologic study conducted by the New Mexico Bureau of Geology and Mineral Resources aimed to construct a more complete hydrogeologic conceptual model at El Morro National Monument (Newton and Kelley, 2019). This paper describes an experiment within that study that focused on the use of continuous soil moisture measurements to assess mechanisms by which water flows through the Zuni Sandstone cliffs of El Morro and the role that these mechanisms may play in the deterioration of the inscriptions.

As mentioned above, inscriptions on the north side of Inscription Rock are deteriorating particularly fast compared to other areas on Monument. Lichen growing on the north side of the promontory accelerates the chemical and mechanical weathering processes that result in the deterioration of the inscriptions in this area. At North Point, the sharp boundary between lichen covered rock and non-lichen covered rock is remarkable (Fig. 3). St. Clair and Knight (2001) identified 43 different species of lichen, mostly on the north side of Inscription Rock and observed significant encroachment by the lichen from the rock surface into the sandstone matrix. They attributed the presence of this lichen to shading by woody vascular plant vegetation around and near Inscription rock, which slows water evaporation and reduces mean summer temperature.

Van Dam and Hendrickx (2007) studied the local hydrogeology at El Morro, using hydrologic and geophysical techniques. They installed shallow piezometers in the vicinity of the historic pool and near North Point and observed an ephemeral shallow water table near the historic pool, with isotopic evidence that this shallow groundwater had likely resided in the cliff for some amount of time before being pushed out by a recent precipitation event. The absence of water in the piezometers near North Point for the duration of the study and electromagnetic induction measurements suggested that an ephemeral water table, similar to that observed near the pool, does not exist in

FIGURE 3. North Point of Inscription Rock. Note the sharp boundary between rock without lichen (left) and rock covered with lichen (right), marked by a vertical fracture. The fence rail in the foreground is about 10 cm thick.

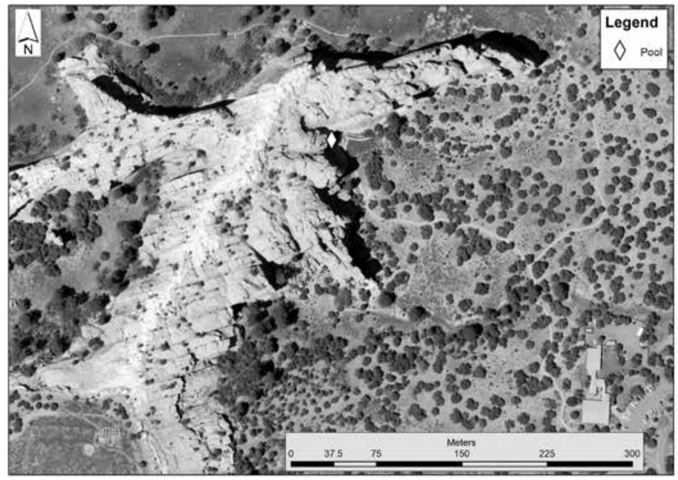

FIGURE 4. Aerial view of Inscription Rock with North Point at the far north-eastern end. The primary joint system can easily be seen, striking to the north-east. The location of the pool is marked with a white diamond.

the vicinity of North Point. However, the electromagnetic induction data also showed an increase in soil moisture towards the cliff both near the pool and North Point. With no shallow groundwater in the vicinity of North Point, Van Dam and Hendrickx (2007) suggested that the rapid deterioration in this area is due to either unique physical and chemical properties of the rock in this area or to a source of water from the top of the cliff.

The very well defined northeast-striking joint system is a prominent feature of the Inscription Rock and has hydrologic implications (Fig. 4). While these fractures are filled with sediment to some extent, they nevertheless must be conduits that provide a relatively quick transport of rain and snow melt from the top of the cliff, downward to the subsurface (Hendrickx and Flury, 2001). Here, we describe an experiment that uses continuous soil moisture data to provide direct evidence of water movement through these preferential flowpaths within the cliff, with implications for processes that lead to the severe deterioration of the inscriptions on the north side of Inscription Rock.

DESCRIPTION OF THE STUDY AREA

Regional and local geology

El Morro, located on the southwestern flank of the Zuni Mountains, is an impressive outcrop made of Middle to Late Jurassic (155 to 165 my) Zuni Sandstone capped by Late Cretaceous (~95 to 96 my) Dakota sandstone and shale. The yellowish-green to tan Zuni Sandstone is composed of well-sorted, angular quartz grains with minor feldspar, cemented primarily by kaolinite. As a consequence of the cementation by clay, the sandstone is soft, easy to carve, and is easily eroded. Large-scale cross-bedding is common in the Zuni Sandstone. The grain sorting and the cross-bedding are characteristic of sand dunes that were part of a dune field that covered much of northwestern New Mexico, northeastern Arizona, southeastern Utah, and southwestern Colorado about 150 Ma ago. Cross (1996) measured the permeability of the Zuni Sandstone at several locations on the monument. Permeability ranged from 0.01 to 204 millidarcies, which correlates to hydraulic conductivities ranging from $1x10^{-10}$ to $2.3x10^{-6}$ m per day.

A Proterozoic-basement cored uplift that formed during Laramide compressional deformation about 75 to 50 my ago, the Zuni Mountains include a pronounced fracture (joint) system that cuts both the Jurassic and the Cretaceous sandstones in the area. The most prominent set strikes NE (65-70°) with relatively regular spacing of 10 to 15 m between fractures. The weaker joint set strikes NW (305-330°). These fractures likely play an important role in the local hydrogeology, specifically in the movement of precipitation downward through the sandstone cliffs.

Although the base of the Zuni Sandstone is not exposed in this area, this unit overlies fine-grained sandstones of the Upper Triassic Rock Point Member of the Chinle Group, which in turn rests on siltstones and mudstones of the Petrified Forest Member of the Chinle Group (NMBGMR, 2003). An apron of younger Quaternary colluvium (rocks block eroded from the cliffs), alluvium (water-lain deposits in arroyos), and wind-blown silt surround the sandstone cliffs.

Hydrogeology

The surface water and groundwater systems considered in this study are local in scale with the primary water source being local precipitation. Annual precipitation on the Monument averages between 35 and 40 cm (Salas and Bolen, 2010). Within the monument, the only perennial surface water is in the historic pool located in an alcove on the south side of Inscription Rock. This pool has been historically documented and appears to have been a stable water source for early Puebloan inhabitants as far back as the 1200s, explorers who visited the area since the early 1600s (West and Baldwin, 1965), and the Monument until 1961. Padgett (1992) describes the history of the pool and how it has changed due to natural and anthropogenic causes. Currently, the pool stores, on average, approximately 757 m^3 (200,000 gallons). Several studies have concluded that most, if not all, of the water in the pool is from surface runoff that cascades off the top of the cliff during rain events (West and Baldwin, 1965; Van Dam and Hendrickx, 2007; Newton and Kelley, 2019). The cliffs surrounding the pool provide shade, especially in the afternoon, which reduces evaporation.

As mentioned above, there is evidence that shallow perched aquifers sometimes exist near the cliff in the vicinity of the pool. Van Dam and Hendrickx (2007) installed six piezometers on the monument, four in the pool area and two near North Point. Depths of the piezometers range from five to 10 ft below the surface. These piezometers are still in place and being used by the Southern Colorado Plateau Network (SCPN) to monitor water levels (Soles and Monroe, 2012). Van Dam and Hendrickx (2007) state that groundwater was not observed during the drilling of the wells, but the moisture content was observed to increase significantly with depth. The observation wells were dry most of the time. However, it was reported that water was present in two wells near the pool on three occasions in August 2006 after rainfall events. Water was observed in one well near North Point on August 8, 2006, after a heavy rainfall. Soles and Monroe (2012) detected water in three of the wells near the pool on different occasions during 2011. Monroe and Soles (2015) noted water in two of the wells near the pool several times in 2012 and 2013. Observed groundwater levels near the pool are all below the pool water surface. Van Dam and Hendrickx (2007) concluded that these shallow perched aquifers were likely ephemeral, existing during wet periods, and were recharged from precipitation on the top of the cliff. Geochemical data indicates that these shallow groundwater systems are not hydrologically connected to the historic pool (Van Dam and Hendrickx, 2007). In addition to the geochemical data, fast groundwater level responses to precipitation events suggest that groundwater recharge to these ephemeral perched aquifers is likely local precipitation that flows from the cliff top through fractures in the Zuni Sandstone (Newton and Kelley, 2019).

Geophysical surveys near North Point and the pool area showed a significant increase in apparent moisture content closer to the cliff (Van Dam and Hendrickx, 2007). Geophysical surveys also showed a larger difference in moisture content between dry conditions in July 2004 and wetter conditions in August 2004 the closer the surveys were to the cliff. While Van Dam and Hendrickx (2007) stated that "the presence of the cliff has a significant impact" on moisture content in the shallow subsurface, they did not discuss what processes cause these observed trends in moisture content. We hypothesize that this increase in moisture in proximity to the cliff is mainly due to water flowing from the top of the cliff through prominent joints. The soil moisture experiment described in this paper was designed to test this hypothesis.

METHODS

On April 26, 2017, we installed ECH_2O-ECTM soil moisture instruments, made by Decagon Services, at nine different sites (Fig. 5, SM3 – SM11). SM10 was located on top of the cliff. All other soil moisture sites were located at the bottom of the cliff in different areas. At each site an instrument was installed at 10- and 30-cm depth. To install these instruments, we dug a small hole (~30 cm in diameter) to the desired depth and laterally inserted prongs in the side of the hole at a specific depth to minimize disruption of the soil. The sensors at each site were connected to a Campbell data logger, which was programmed to log soil moisture and temperature data every 15 minutes. We removed all instruments on October 5, 2017.

These probes indicate volumetric soil moisture (volume of water/ total volume of soil) by measuring the dielectric permittivity (the ability of a substance to hold an electric charge) of the surrounding medium. Because the dielectric permittivity of water is much greater than other constituents of soil, a change in dielectric permittivity is directly related to a change in water content. Prior to installing these instruments, we collected soil samples from each site and calibrated each instrument to the specific soil associated with each site. Instrument calibration in the lab entailed correlating raw millivolt outputs to known volumetric water contents. Average raw millivolt readings were recorded for different known water contents, beginning with a dry soil sample and subsequent incremental increases in water content. The resulting linear regression for each instrument was then used to calculate volumetric soil moisture at each instrument site. As will be seen in the discussion about these data below, for reasons unknown, some instruments pro-

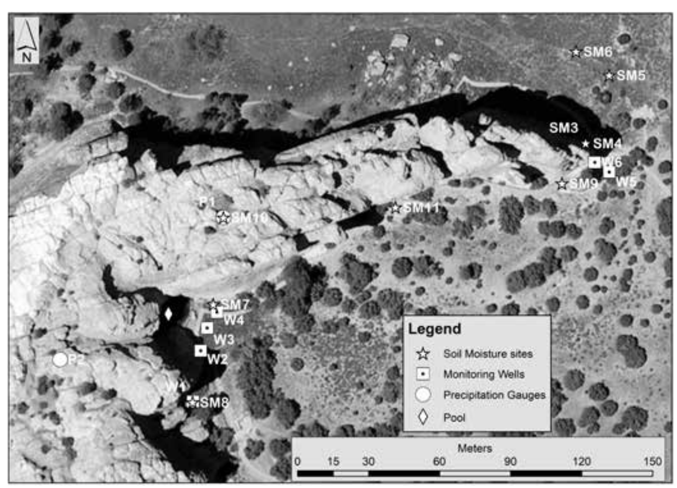

FIGURE 5. Locations of piezometers (W1–W6), soil moisture sites (SM3–11), and a precipitation gauge and collector (P1 and P2). Soil moisture sites 3 and 4 are only about six meters apart.

duced somewhat noisy data sets with fairly large fluctuations from measurement to measurement. Fortunately, seasonal trends and responses to rain events can still be identified in the time series datasets that are discussed below.

The storage and movement of water in soils is largely controlled by soil characteristics, such as grain-size distribution, bulk density, organic content, etc. We conducted wet sieve analyses to characterize the grain-size distribution, and we measured the soil bulk density using the core method (Al-Shammary et al., 2018). We did not measure organic content. A precipitation collector was installed near the soil moisture site on top of the cliff and daily precipitation readings were collected from the weather station run by the National Park Service on the monument.

RESULTS

Continuous soil-moisture data were collected at all locations between April 27 and October 5, 2017. This experiment aimed to compare fluctuations in soil moisture at areas near the base of the cliff to soil-moisture fluctuations at control points, thus to some degree indicating the processes by which water is introduced to the soil. Table 1 shows site descriptions and sieve-analysis results for each soil-moisture site.

Sites SM5 and SM6 are located tens of meters away from Inscription Rock to the northeast of North Point. Based on the assumption that all soil moisture comes from local precipitation that falls directly on the soil surface or local surface runoff from the surrounding topography, these sites, far from Inscription Rock, were designated control sites. The vegetation was primarily the low-growing Winterfat Dwarf shrub (*Krascheninnikovia lanata*; Salas and Bolen, 2010); thus, these sites are exposed to the sun most of the day. SM-6 was located on a shallow slope out in the open, and SM5 was located at the bottom of a shallow depression or channel that may have accumulated some surface runoff during large rain events. The highest water content was observed at 10-cm depth in response to precipitation events in late April and early May while antecedent soil moisture was relatively high, likely due to cumulative infiltration of winter rain and snowmelt with low evaporation rates. This high antecedent soil moisture during April and May was observed for almost all sites. The May rain event produced peak soil moisture values at 10 cm of about 0.36 and 0.23 for SM5 and SM6, respectively (Fig. 6). Soil moisture at ten centimeters depth then decreased gradually to about 0.05 at both sites due to increasing temperatures. Monsoon storms beginning in July resulted in an increase in water content with peak values of 0.2 and 0.16. Subsequent drying was observed from August through late September when another storm caused values to increase to about 0.15 for both sites (Fig. 6). For both sites, soil moisture at 30-cm depth mostly shows a drying trend with very little response to precipitation events. For SM5, this drying trend is more drawn out over time and there are small responses to some of the bigger storm events. Soil moisture data for the SM10 (Appendix 1), located on the top of the cliff, were very similar to those for SM6. These data strongly suggest that most soil water is lost to evapotranspiration, with very little infiltration past 10 cm for most precipitation events during the monsoon season.

SM7 was located very close to the cliff near the historic pool, and SM8 was located close to the cliff in an alcove just south of the pool. Piezometers have shown evidence of an ephemeral water table that develops during periods of heavy rainfall at both of these sites. Soil moisture data at these two sites show very different responses to precipitation than those observed at the sites further away from the cliff and on top of the cliff. Figure 7 shows soil moisture fluctuations for SM7 and SM8. Missing data for SM8 is due to technical issues with

Table 1. Site descriptions and wet-sieve grain-analysis data.

Site number	Site description	% medium sand	% fine and very fine sand	% silt and clay	Soil Texture
SM3	North Point – east side of fracture at base of cliff	3.3	81.3	15.4	Loamy very fine sand
SM4	North Point – west side of fracture at base of cliff	1.3	85.6	13.1	Loamy very fine sand
SM5	Drainage north of North Point >10 m from the cliff	1.6	74	24.4	Very fine sandy loam
SM6	West of EM-9005 on grass-covered slope >10 m from the wall	4.4	85.5	10.1	Fine sand
SM7	Near monitoring well EM-0003, below pool proximal to cliff wall	1.1	83	15.9	Loamy, very fine sand
SM8	In alcove just south of the pool at base of cliff	0.6	88.6	10.8	Very fine sand
SM9	South side of North Point below Arran Lopez inscription at base of cliff	1.7	80.9	17.4	Loamy very fine sand
SM10	At top of cliff in shallow depression	2.5	82.8	14.7	Loamy fine sand
SM11	At interpretation point 10 along inscription trail, beneath overhanging cliff wall	1.2	82.1	16.8	Loamy fine sand

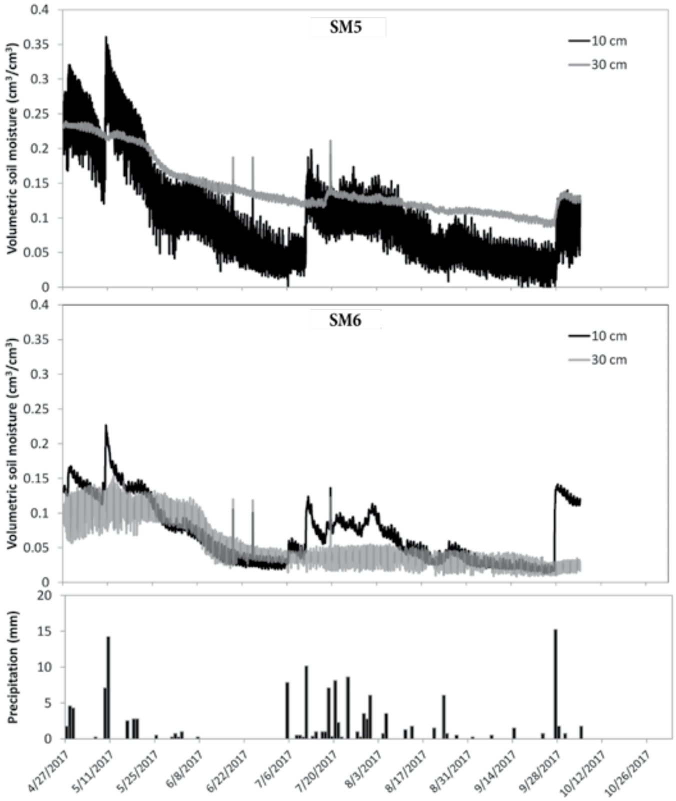

FIGURE 6. Soil moisture time series for SM5 and SM6. The bottom graph shows local precipitation amounts. Although soil moisture datasets for SM5 at 30-cm depth and for SM6 at 10-cm depth show considerable noise, which is likely related to the specific instruments, the signal/noise ratio is still good enough to identify seasonal trends and correlations between soil moisture and precipitation events.

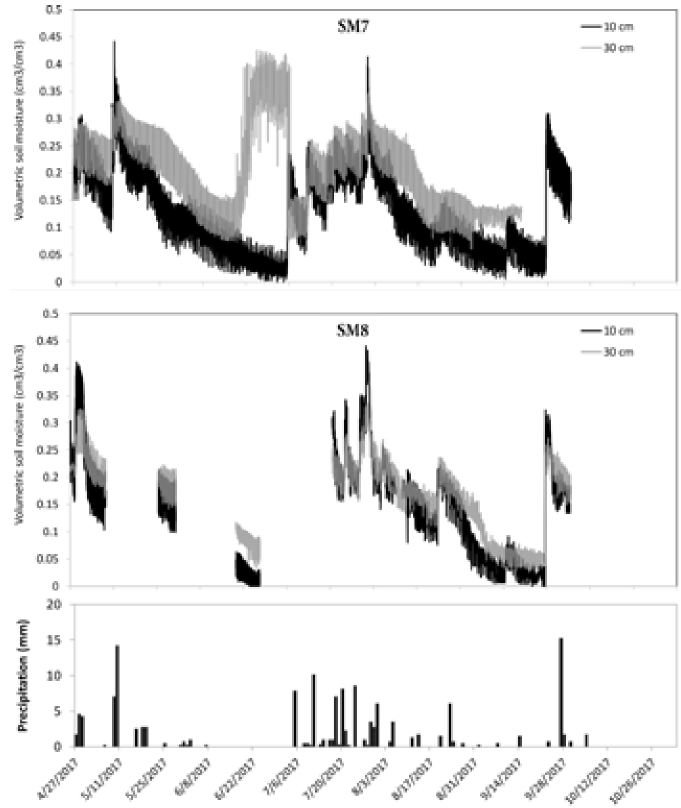

FIGURE 7. Soil moisture time series for SM7 and SM8. The bottom graph shows local precipitation amounts.

the data logger. Initial trends at 10-cm depth were similar to those seen for control sites but with slightly higher peak values for April and May storm events (>0.4). Subsequent drying resulted in soil moistures decreasing to levels less than 0.1 at the shallow depths by early July. We do not have an explanation for the anomaly observed at 30-cm depth for SM7 where the soil moisture abruptly increases to values as high as 0.45 in mid-June and remains high through early July. We speculate that this is related to an event where water from the pond was diverted to test a nearby newly built drainage structure. However, we have not been able to confirm with Monument staff that this actually happened. During the monsoon season at both of these sites, soil moisture at 10-cm depth responded very quickly to some individual storms but also showed a cumulative increase with maximum values occurring in late August as the monsoons began to wane. Soil moisture during the monsoon season at the shallow depths climbed to values higher than 0.40, which is much higher than those observed during this time period for sites discussed previously. Interestingly, unlike the sites discussed above, soil moisture at 30-cm depth for SM7 and SM8 responded to rain events during the monsoon season almost identically to the responses observed at 10 cm, both in terms of timing and magnitude.

SM9 was located near the trail going east just before North Point, within one meter of the cliff wall. Soil moisture fluctuations at this site were almost identical to those observed for SM6, which is the control site out in the open. Soil moisture at both depths decreased during May and June due to increasing temperatures (Fig. 8). Monsoon rains significantly increased soil moisture at 10-cm depth but had little effect on soil moisture at 30-cm depth. Soil moisture at both depths never rose above 0.2 (Fig. 8). It appears that for this site, the close proximity to the cliff did not affect soil moisture fluctuations.

Soil moisture site SM11 was located along the Inscription Rock trail within one meter of the cliff, underneath a small overhang. This overhang significantly decreases the amount of rain that reaches the ground surface. There was no significant change in soil moisture for the duration of this study (Appendix 2), and soil moisture data at this site at both depths did not go above 0.03.

We placed soil moisture instruments SM3 and SM4 within one meter of the cliff wall at North Point, shown in Figure 2, in the area where the wall is bare and where the wall is covered with lichen, respectively (Fig. 9). These sites are within three meters of each other, and the first two months of soil moisture fluctuations are almost identical with the typical high initial values and gradual decrease going into summer months (Fig. 10). However, soil moisture fluctuations exhibited different characteristics during the monsoon season. At both sites the first two large storms in July resulted in soil moisture increases at 10-cm depth but not at 30 cm. For storms that occurred during late July and early August, soil moisture at 30 cm did increase at both sites but to a much larger extent for SM4, located

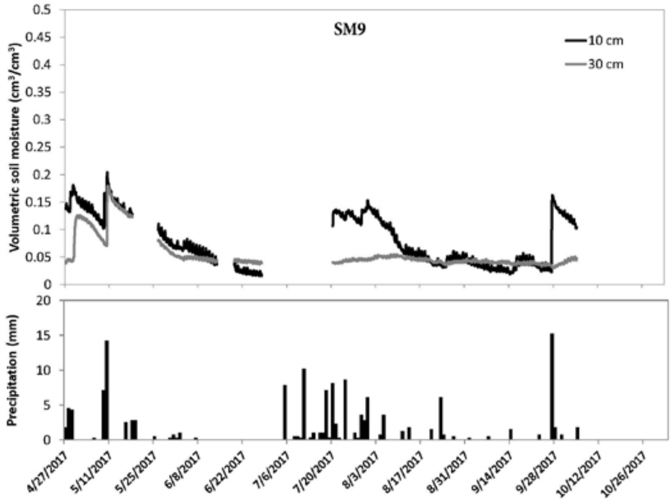

FIGURE 8. Soil moisture time series for SM9. The bottom graph shows local precipitation amounts.

FIGURE 9. Site SM3 is under the rock in the foreground close to the wall with little or no lichen. SM4 is located under the rock in the background next to the wall that is covered by lichen. Graduate student, Kylian Robinson is seen finishing up instrument installation.

adjacent to the lichen-covered wall. At SM4, soil moisture values at 30 cm were of the same magnitude as values observed at the shallow depth, and similar to what was observed for SM7 and SM8 near the pool. The soil moisture responses observed at 30-cm depth for SM3, located adjacent to the bare wall, were slightly delayed and at a much smaller magnitude with respect to the response seen at 10-cm depth. The soil moisture fluctuations observed for SM3 were similar to those of SM6, where the only source of soil moisture was local precipitation that fell directly on the surface (Figs. 6, 10). The 30-cm response to the large storm in September was also much more pronounced for SM4 than for SM3 (Fig. 10). These data suggest that different mechanisms control soil moisture conditions at these two locations, which are in close proximity to each other.

After almost two months of continuous dry conditions, a major precipitation event of 15 mm occurred on September 27. The sudden change or absence of change in response to this storm at each soil moisture sensor provides more support for our conceptual hydrologic model discussed in the next section. The soil textures indicate that the soil water holding capacities of the soils are between 10 and 20 volume percent. A storm of 15 mm could increase the moisture in the top 10 cm of the soil by about 15 volume percent but wouldn't significantly affect soil moisture at 30-cm depth. Observed soil moisture changes due to the September 27 storm were analyzed to estimate the amount of water that infiltrated into the soil due to the storm. The change in volumetric water content at 10-cm depth was assumed to represent the total amount of infiltration in the top 10 cm of soil. The observed change in soil moisture at 30-cm depth was assumed to represent the total amount of infiltration between 0- and 30-cm depth. The amount of water that infiltrated between 10- and 20-cm depth was estimated by linear interpolation. Results of these calculations are shown in Table 2. The location description in Table 2 includes the orientation of the cliff wall with respect to strike of the primary joint system (perpendicular or parallel). The significance of this relationship will be discussed in the next section.

For the control sites SM5 and SM6, we estimated total infiltration to be 16.5 and 18 mm respectively, slightly larger than the total amount of precipitation. We are likely overestimating actual total infiltration, and therefore the total amount of infiltration in both control points is likely equal to the total precipitation amount (15 mm). For the two sites close to the pool, SM7 and SM8, which are located close to the cliff wall and are perpendicular to the joints, total infiltration was estimated to be much greater than precipitation. Total infiltration for SM8 was estimated to be 75 mm, about five times that of total precipitation. The total amount of infiltration to 30-cm depth for SM7 could not be estimated due to technical issues with the instruments. However, we estimated the amount of water infiltrating into the top 10 cm to be 26 mm, and the total infiltration to 30-cm depth is likely comparable to that estimated for SM8. For SM9, located close to the wall, which is parallel to joint strike,

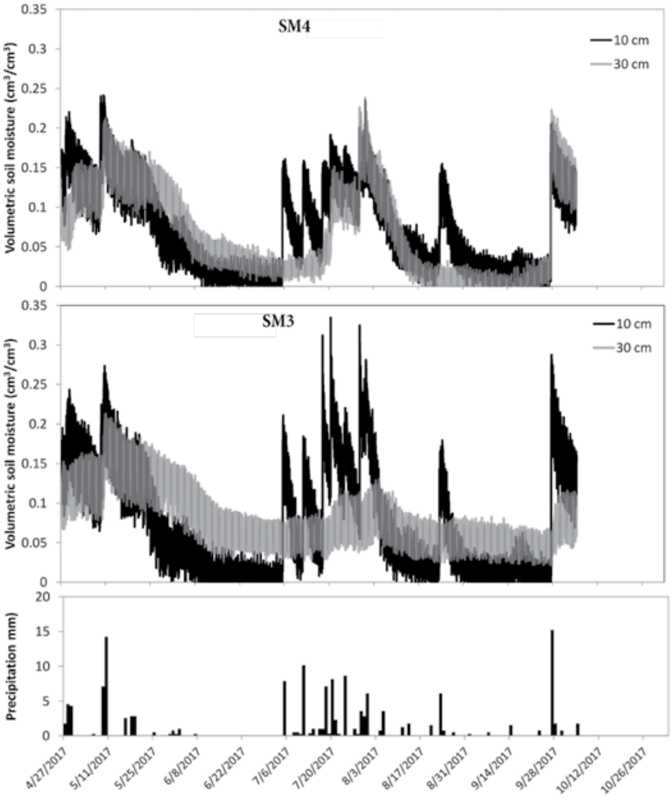

FIGURE 10. Soil moisture time series for SM3 (Northpoint near bare wall) and SM4 (North Point near lichen-covered wall). The bottom graph shows local precipitation amounts.

we estimated total infiltration to be 19.5 mm, which is similar to estimates for the control sites, suggesting that total infiltration equal total precipitation. We estimated total infiltration to be almost zero (about 1 mm) for SM11, located near the wall (parallel to joint strike) under a small overhang. For SM3 and SM4, located at North Point where the wall is perpendicular to joint strike, we estimated total infiltration to the depth of 30 cm to be 45 and 57 mm respectively. As was observed at sites near the pool (SM7 and SM8) both of these estimates of total infiltration are much larger than total precipitation. Interestingly, infiltration estimated for SM4, adjacent to the lichen-covered wall was larger than infiltration estimated for soil near the bare wall. For SM10, located on the top of the cliff in a small sediment-filled depression, total infiltration was estimated to be 43.5 mm. This large infiltration amount indicates that significant runoff accumulates in this depression.

DISCUSSION

Hydrogeologic Conceptual Model

Van Dam and Hendrickx (2007) observed an increase in soil moisture as they moved closer to the cliff in the vicinity of the pool and near North Point. Similarly, we observed average soil moisture values near the cliff in the vicinity of the pool (SM7 and SM8) and near North Point (SM3 and SM4) to be significantly higher than those observed at control points away from the cliff (SM5 and SM6), especially during monsoon season. However, sites SM9 and SM11, which were also in very close proximity to the cliff wall, did not exhibit higher soil moisture value compared to the control points. Figures 11 and 12 show that sites SM7, SM8, SM3 and SM4 are all located in areas where the cliff face is perpendicular to the strike of the primary joint system, and SM9 and SM11 are located along the northeast trending cliff wall that is parallel to the joint strike. This observation strongly suggests that additional soil moisture observed near the cliff in some of these sites is due to the percolation of water from the top of the cliff downward through the vertical fracture that defines the primary joint system. Figure 13 shows our conceptual model of the local cliff hydrogeologic system. Most precipitation and snowmelt at the top of the cliff either runs off the side of the cliff (in this case filling the historic pool) or into the large fractures at the surface. Water is stored in the pores of the sediments that partially fill these fractures. With the addition of runoff from monsoon precipitation, hydraulic head in the fractures increases, causing water to

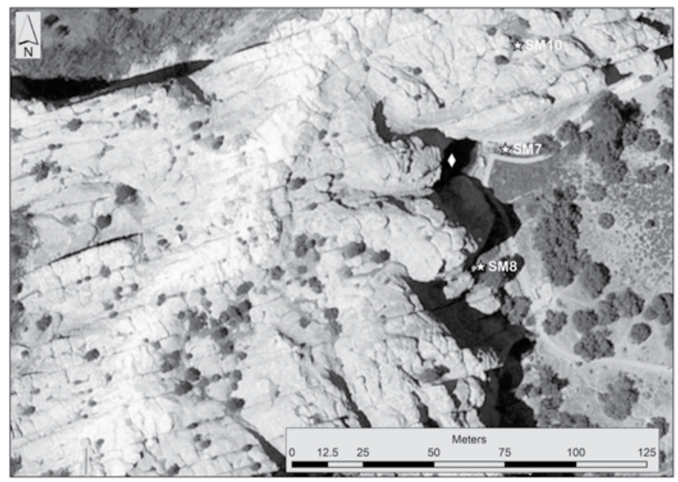

FIGURE 11. Satellite photograph of Inscription Rock in the vicinity of the pool (white diamond), SM7, and SM8. SM10 is on top of the cliff in a small depression filled with sediment (gray patch north of the SM10 site on this image). Joints that likely transport water downward through the cliff to the subsurface near the base of the cliff are clearly visible in this image.

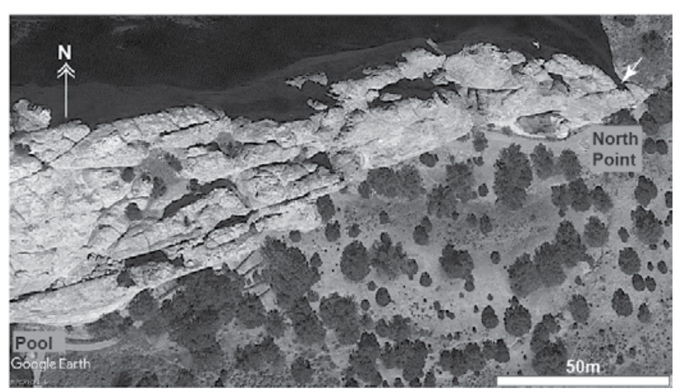

FIGURE 12. Google Earth image of Inscription Rock within the vicinity of North Point. The white arrow denotes the fracture that is in between SM3 and SM4.

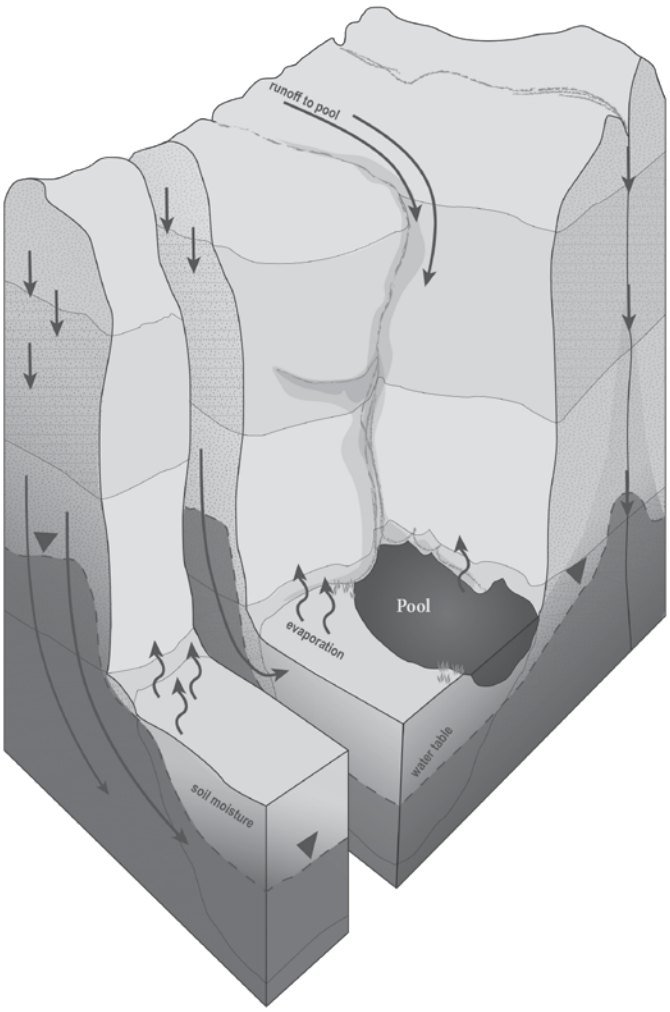

FIGURE 13. Conceptual model illustrating hydrogeologic processes at El Morro National Monument near the historic pool. Most precipitation and snowmelt at the top of the cliff either runs off the side of the cliff (in this case filling the historic pool) or into the large fractures at the surface. Water stored in sediment that partially fills fractures can be mobilized by an increase in the head gradient due to the addition of water by large snowmelt or storm events. The water percolates downward through fractures to contribute to soil moisture and may sometimes provide enough water to form an ephemeral shallow perched aquifer (dashed water table) at the base of the cliff.

percolate downward. This water contributes to soil moisture at the base of the cliff, as evident by the observed soil-moisture increases at 30-cm depth. During very wet periods, enough water will accumulate to form a shallow perched aquifer as is observed near the pool. The apparent absence of an ephemeral perched aquifer near North Point is discussed below.

Soil Moisture Responses at North Point

Soil moisture fluctuation data described above provide direct evidence of the movement of water from the top of the cliff to unconsolidated sediments at the base of the cliff via northeast-southwest trending joints. Soil moisture time series datasets for sites SM3 and SM4 (Fig. 10) and estimated infiltration volumes for these sites (Table 2) indicate that water from the top of the cliff is moving through these fractures and contributing to soil moisture at the base of the cliff at North Point, where lichen is impacting inscriptions (Fig. 3). The soil moisture trends observed for SM3 and SM4, which are only three meters apart, have implications for the presence of lichen and increased deterioration rates of inscriptions on the north side of Inscription Rock near North Point. Similar soil moisture values and responses to precipitation events in May for both SM3 and SM4 (Fig. 10) at both measurement depths indicate similar volumetric contributions from fracture flow to soil moisture at both sites. However, for subsequent precipitation events in late July and on September 27, fracture flow contributions to soil moisture for SM4 (near lichen-covered wall) were significantly higher than those observed for SM3 (near bare wall). This observation indicates that under some conditions, more water is flowing though fractures above the lichen-covered wall than those above the bare wall. This difference in apparent fracture flow volumes at these two sites may be due to different water supply volumes to fractures and/or differences in water loss or depletion rates from the fractures.

Although we think that the observed differences in soil moisture fluctuations for SM3 and SM4 are due to factors that control the transport of water through fractures and the sandstone matrix in the cliff, which are discussed below, other possibilities should also be considered. Grain-size analyses showed similar distributions for both sites (Table 1), and therefore, we would expect to see similar soil moisture trends if local precipitation was the only source of soil moisture. However, as seen in Figure 9, vegetation at these sites is quite different. With more sun exposure, the area adjacent to the bare rock wall (SM3) is characterized by mostly bare ground with scattered small shrubs. For the area adjacent to the lichen covered wall (SM4), less sun exposure due to the northern aspect of the wall and shade by nearby trees, results in the ground being mostly covered with grasses and other low-lying plants. It is possible that interactions between the vegetation and soil may significantly affect soil water parameters, including infiltration rates. More research should be done to assess these ecohydrological processes.

Controls on water supply volume to fractures

The amount of water that flows through fractures from the top of the cliff to sediments at the base of the cliff is likely related to characteristics of fractures within the cliff and how they influence water flowpaths. Fractures on top of the cliff near North Point (Fig. 12) are not as well defined and continuous as those above the pool area (Fig. 11). This difference alone can explain why there appears to be more water flowing through fractures and contributing to soil moisture near the pool (SM7 and SM8) compared to the area near North Point (SM3 and SM4). In addition to limiting the volume of fracture flow near North Point, the poorly defined fractures may also exhibit lower vertical permeability compared to the better defined fractures above the pool area. Therefore, not only might there be less water flowing through fractures at North Point compared to those above the pool, water may also move at

TABLE 2. Estimated infiltration amounts for the 15-mm rainfall during the September 2017 storm event, based on volumetric soil moisture measurements before and after the storm.

			Volumetric water content (%)			*Estimated infiltration (mm)*			
Site	**location**	**Depth (cm)**	**Pre-storm**	**Post-storm**	**Difference**	**0 - 10 cm**	**10 - 20 cm**	**20 - 30 cm**	**Total**
SM3	Near cliff at North Point, bare wall, perpendicular to joints	10	2%	27%	25%	25	15	5	45
		30	4%	9%	5%				
SM4	Near cliff at North Point, lichen covered wall, perpendicular to joints	10	2%	20%	18%	18	19	20	57
		30	2%	22%	20%				
SM5	> 10 m from cliff, control site, shallow depression	10	3%	10%	7%	7	5.5	4	16.5
		30	9%	13%	4%				
SM6	> 10 m from cliff, control site, gentle slope	10	2%	14%	12%	12	6	0	18
		30	2%	2%	0%				
SM7	Close to pool, near cliff, perpendicular to joints	10	3%	29%	26%	26	NA	NA	> 26
		30	NA	NA	NA				
SM8	Close to pool, near cliff, perpendicular to joints	10	2%	31%	29%	29	25	21	75
		30	4%	25%	21%				
SM9	Close to cliff, parallel to joints	10	2%	15%	13%	13	6.5	0	19.5
		30	3%	3%	0%				
SM10	Top of cliff, shallow depression	10	2%	20%	18%	18	14.5	11	43.5
		30	4%	15%	11%				
SM11	Close to cliff, under overhang, parallel to joints	10	0%	1%	0%	0.7	0.35	0	1.05
		30	1%	1%	0%				

slower velocities in fractures at North Point compared to those above the pool area.

Further examination of fractures at North Point can help to explain differences in apparent supply volumes to fractures associated with SM3 versus those associated with SM4. The fracture that appears to be in between soil moisture sites SM3 and SM4 (Fig. 12) exists as a fracture in a very small section of rock near the tip of North Point and a section of the cliff just east of the pool. In between these two sections of cliff, the inner wall of this joint is exposed as the cliff face (facing south). The small extent of this joint at North Point greatly limits the amount of precipitation that can be diverted to it and any small fractures to the south that may contribute to soil moisture at SM3. Fractures to the north are more extensive and may be connected to other fractures to the west. These fractures can potentially transport more precipitation that falls on the top of the cliff to the subsurface near the base of the cliff near SM4.

Depletion of water stored in fractures

The fact that apparent fracture flow contributions to soil moisture at SM3 and SM4 changed with time indicates that water stored in sediments that partially fill the fractures can be depleted. Fracture flow in early May for SM4 is indicated by a soil moisture increase at 30-cm depth. Water was apparently depleted from storage within the fractures during the dry period between May and July, as the fracture flow contribution to soil moisture at 30 cm was not apparent in early July when the monsoon season began. Early monsoon rains apparently replenished water being stored in fractures, and the fracture flow contribution to soil moisture was once again observed for precipitation events in late July and early August as significant increases in soil moisture at 30-cm depth. Water in these fractures was apparently depleted fairly quickly with a decrease in the frequency of storms, as we observed a soil moisture response to a storm in late August at 10 cm but not at 30-cm depth. The large storm in late September appears to have refilled the fractures and transported water to the soil at the base of the cliff. This temporal trend in soil moisture was observed for SM3 (the site near the bare wall at North Point) but with much smaller fracture flow contributions to soil moisture for late monsoon rains and the late September event.

After precipitation events, which drive water to percolate downward through sediments that fill fractures, the volume of water that is stored in these sediments is controlled by the water-holding capacity, which is probably similar to that for sediments at the base of the cliff (10 to 20 volume percent). Depletion of this stored water may be due to evaporation from the sediment surface within the fractures, transpiration by trees that have roots in the fractures, and lateral movement of water into the adjacent sandstone matrix. Evaporation of pore water from sediments will only significantly deplete water from the top 30 cm or so of the fracture-filling sediments. As seen in Figure 4, vegetation is scarce on top of the cliff, limiting the effects of transpiration on the volume of water stored in the fractures. Lateral movement of water into the sandstone matrix is a slow process driven by diffusion due to a water potential gradient.

The apparent depletion of water from storage in fractures was not observed at sites near the pool (SM7 and SM8) where all precipitation events showed fracture-flow contributions to soil moisture. So, why do we see significant depletion of stored water in fractures at North Point and not in fractures near the pool? We think the depletion of water stored in fractures above North Point is mostly due to the lateral movement of water from sediments in fractures through the adjacent sandstone matrix to the surface of the cliff wall. The reason this process may lead to significant depletion of water stored in fractures at North Point and not in fractures above the pool is related to the total storage volume in fractures (smaller water supply to these fractures and smaller, less developed fractures as discussed above), vertical permeability in fractures (lower fracture-flow velocities as discussed above), and the proximity of the stored water to the vertical surface of the cliff wall. Water that moves through the sandstone matrix and reaches the cliff wall surface quickly evaporates. If the stored water is in close proximity to the wall surface, continuous evaporation from the wall surface and near-surface pores may result in a sufficient water potential gradient to transport a large enough volume of water relative to the stored volume to significantly deplete water stored in these fractures during dry and hot periods. Because both sides of the arm of the cliff that forms North Point are essentially fracture faces, diffusive transport of water through the matrix from nearby parallel fractures will draw water to the cliff wall surface. In contrast, diffusive transport of water stored in fractures near the pool moves water into the massive sandstone matrix and not towards the cliff wall surface. Higher evaporation rates on the bare wall surface above SM3 due to more sun exposure compared to the adjacent lichen covered wall help to explain the smaller fracture-flow contribution to soil moisture for SM3 compared to SM4.

CONCLUSIONS

Soil moisture data shows strong evidence that the presence of the cliff affects the amount of water infiltrating into the soil in some areas. At control sites away from the cliff where local precipitation that falls on the surface is the only source of soil moisture, volumetric water content increased at 10-cm depth in response to individual storms with little or no soil moisture response at 30 cm. Total estimated infiltration for a storm in September 2017 at control sites was roughly equal to the total amount of precipitation. In areas near the cliff where the cliff face is perpendicular to the strike of the primary joint system (northeast-southwest), soil moisture increased significantly (by similar magnitudes) at both 10- and 30-cm depth as responses to large storms or groups of storms with total estimated infiltration for the September storm greatly exceeding the total precipitation amount. This additional soil moisture was not observed at sites near the cliff in areas where the cliff face is parallel to joint strike. This additional source of soil moisture observed at sites near the cliff where the cliff wall is perpendicular to the primary joint strike is direct evidence of water moving from the top of the cliff through fractures to unconsolidated sediments at the base of the cliff. Water is stored in the pores of sediment that partially fills fractures. During a precipitation event, water runs off into fractures, increasing hydraulic head in the fractures, causing water to move downward into unconsolidated sediments at the base of the cliff. We observed this fracture flow contribution to soil moisture at two sites near the pool and at two sites near North Point. These data were used to construct the hydrogeologic conceptual model shown in Figure 13.

At North Point, soil moisture was measured at two sites within three meters of each other on either side of a vertical fracture in the cliff that defines a boundary with lichen covering the wall on one side and bare rock and no lichen on the other side. Both sites exhibited evidence for fracture-flow contribution to soil moisture, although to a smaller degree than was observed at sites near the pool. The site adjacent to the wall with lichen showed higher fracture flow contributions to soil moisture than the site near the bare wall. Fracture-flow contributions to soil moisture at both of these sites changed with time, indicating water was being depleted from storage in sediments within the fractures during periods of no precipitation and high temperatures. Storage depletions were not observed at sites near the pool. These apparent depletions from storage in the fractures were observed to be higher for soil near the bare wall. Analysis of fractures in aerial photographs (Figs. 11 and 12) suggests that fracture characteristics (development, size, connectivity, etc.) likely control the amount of water that is stored in fractures and how quickly it moves through the fractures to underlying sediments. Apparent depletions from storage in fractures observed at sites near North Point are likely due to water moving laterally through the sandstone matrix to the nearby surface of the cliff face where it quickly evaporates. Higher evaporation rates on the bare wall due to higher sun exposure causes the observed higher storage depletion rates.

Water moving downward from the cliff top through fractures to the unconsolidated sediments at the base of the cliff is likely an important mechanism by which water ultimately comes in contact with the inscriptions in certain areas. It appears that in some locations, such as the area near the pool, percolation of water through fractures contributes a significant amount of water to the unsaturated soil, and at times of high snow melt or rainfall, these fractures can transmit enough water to develop a shallow perched aquifer in the alluvium. Water may move upward through the sandstone matrix of the cliff by capillary action from the ephemeral water table or from the soil to come in contact with inscriptions. However, the more important mechanism by which water reaches the inscriptions, specifically related to the cliff face on the north side of Inscriptions Rock near North Point, likely involves the movement and storage of water moving in fractures that are close to the wall surface. This water can potentially move slowly through the sandstone matrix mainly driven by capillary action and a water potential gradient resulting from the evaporation of water that reaches the rock surface. Along the arm of the cliff that forms North Point (Fig. 12), fractures are not as well defined and continuous as observed in other areas such as the area above the pool. Water may not be transported downward as easily, and therefore the amount of water that does make it to the bottom of the cliff is insufficient to form an ephemeral perched saturated zone in the alluvium at the base of the cliff. Much of this water may be "trapped "in dead-end fractures in the rock, where it is diffusively transported through the rock matrix to the cliff face. The combination of these processes and lower evaporation rates due the northern aspect and shade by nearby trees likely makes the area on the north side of Inscription Rock more hospitable to lichen that is currently contributing to the deterioration of inscriptions in the area.

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Appendices can be found at http://nmgs.nmt.edu/repository/index.cfml?rid=2020006