Mosaic desert pavement influences water infiltration and vegetation distribution on fluvial fan surfaces

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Abstract

Desert pavements are critical for maintaining ecological stability and promoting near-surface hydrological cycle in arid regions. However, few studies have reported the desert pavements on ecological on fluvial fans. Although desert pavement surfaces appear to be barren and flat, we found that the surfaces were featured by mosaic pattern of desert pavement (DP) and bare ground (BG). In this study, we investigated the effects of mosaic DP on water infiltration and vegetation distribution at six sites (i.e. one on the hillside and five in the sectors of fluvial fans) along a southwest belt transect on the fluvial fans in the Northern Linze County, in the middle of Hexi Corridor. The results showed that significant differences of Mosaic DP between hillside and sectors of fans were found in pavement thickness, thickness of vesicular horizon (Av thickness), particle composition and bulk density, rather than soil moisture content (SMC), gravel coverage and surface gravel size. The mosaic DP can inhibit water infiltration by pavement layer, where the sorptivity (S), initial infiltration rate (i_{int}) and steady- state infiltration rate (i_{sat}) and infiltration time (T) averaged 1.30 cm/min$^{-0.5}$, 5.03 cm/min, 0.23 cm/min, and 12.76 min respectively. If pavement layer was scalped, the S, i_{int} and i_{sat} increased by 0.75 cm/min$^{-0.5}$, 2.90 cm/min and 0.13 cm/min, respectively, and the T was shortened by 5.34 min. Water infiltration was mainly controlled by the pavement layer thickness (+), Av thickness (-), surface gravel coverage (-), and fine earth (+) and fine gravel (-) of pavement layer. Mosaic DP grew less shrubs than mosaic BG where distributed plenty of herbs. It can be concluded that desert pavements can keep vegetation stability by self-regulating rainfall. This study would deepen our understanding of the eco-hydrological cycle of pavement landscape in arid regions.

Keywords

Desert pavement, mosaic surface, water infiltration, vegetation distribution, fluvial fan

1 | INTRODUCTION

As the common feature on the landscape scale in arid regions, desert pavements are found in the weathered debris mantles, pluvial lake benches, alluvial terraces and fluvial fans (Dietze et al., 2016; Goudie, 2013). Desert Pavements are the thin layer of closely packed gravel fragments that embed in the finer vesicular horizon (Av horizon) (Knight & Zerboni, 2018). Pavement surfaces can protect underlying soil from wind and water erosion (Hupy, 2004), and can capture dust into topsoil (Adelsberger et al., 2013). More importantly, the surfaces can influence ecological structure and near-surface hydrology by reducing infiltration rates and increasing runoff (Meadows, Young, & McDonald, 2008). However, pavements have suffered from damage and even an irreversible change in land use patterns because of the frequent human activities (i.e. sand mining, reclaiming virgin land, afforestation et al.) in the past few decades, particularly in China. Therefore, protecting and utilizing desert pavements, a thorough understanding of their effects on the hydrological and ecological processes is needed.

Desert pavements sustain vegetation survival and growth by the scarce and unpredictable rainfall events in arid regions (Haff, 2001). Occurrence of rainfall events can generate local recharge or runoff that is delivered to other focus areas (micro-landform lowlands or ephemeral wash channels) (Pietrasiak, Drenovsky, Santiago, & Graham, 2014). Because of the low infiltration, pavements can cut down on water that permeates into plant roots and stores the subsoil (Michael H. Young, McDonald, Caldwell, Benner, & Meadows, 2004). Whereas, this part of water is lost rapidly and may carry soluble salts up to the subsoil beneath the pavements under high evapotranspiration conditions (Abrahams & Parsons, 1991; Poesen, Ingelmo-Sanchez, & Mücher, 1990). Therefore, plants suffer from the threat to soil drought and salt stress so that vegetation is sparse on pavement surfaces (Kaseke et al., 2012; Rostagno & Degorgue, 2011). Although desert pavements cover a large area with negligible relief and scarce vegetation (Bowman, 2018; Pietrasiak et al., 2014), pavement surfaces exhibit that the “island” of desert shrub and bare ground (BG) are surrounded by well-developed desert pavement (DP), which are called surface mosaics (Musick, 1975; Wood, Graham, & Wells, 2002). Wood, Graham, and Wells (2005) illustrated that distinctive surface mosaics can control pedogenic processes and vegetation distribution. However, little studies focus on surface mosaics so that their eco-hydrological processes are not fully understood. Therefore, effects of the surface mosaics on the eco-hydrological processes should be further investigated.

Vegetation distribution on the pavement surface relates closely to water infiltration, which can regulate water recharge and runoff (Hamerlynck, McAuliffe, McDonald, & Smith, 2002; Wood et al., 2005). Water infiltration varies considerably depending on the pavement layer and Av horizon. With the age of fluvial fan surface, water infiltration decreases due to the development of Av horizons where silt and clay contents were accumulated within the topsoil (McDonald, Pierson, Flerchinger, & McFadden, 1996; Michael H. Young et al., 2004). M. H. Young (2003) indicated that the infiltration reduction through the soil peds can be compensated by an increasing preferential flow, which can flow down along the soil ped faces within the well-developed Av profiles. Meadows et al. (2008) indicated further that water infiltration is dominated by the matrix flow pathway on the younger and less-developed surface, but by the preferential flow pathway on the older and well-developed surfaces. Gravel coverage can promote water infiltration on natural pavement surfaces, but it can also reduce infiltration when the surfaces are crunched by vehicular traffic (Iverson, 1979). Abrahams and Parsons (1991) attributed the cause to the position of gravel whether resting on the soil surface or setting in the soil, which was verified by Poesen et al. (1990). Chen, Yin, Miller, and Young (2009) considered that the pavement layer is not the restrictive layer for water infiltration processes with method of field rainfall simulation. Although water infiltration of pavements has been researched intensively, their infiltration mechanism has not been fully appreciated due to lack of understanding of pavement layer. Therefore, the mechanism of pavement layer on water infiltration required to be identified.

Therefore, the purposes of this study are a) to quantify the soil properties of mosaic DP; b) to evaluate the water infiltration capacity of mosaic DP and its influencing factors, and c) to illustrate the effects of mosaic DP on vegetation distribution. This study would provide a new perspective for understanding the pavement landscape on the fluvial fans in arid regions and improve the decision-making for the administrative department to manage the fluvial fans.

2 | MATERIALS AND METHODS

2.1. Study area and sites

This study was conducted in 2019- 2020 on the fluvial fans of Northern Linze County (39°23′–39°31′ N, 100°5′–100°13′ E), which belongs to the hilly regions in the middle of Hexi Corridor, Northwest China (Figure 1a). The climate is a temperate continental climate with hot-arid summer and cold winter. The mean temperature is 7.6℃ with a maximum of 39.1℃ and a minimum of -27.3℃, respectively. The annual mean precipitation is 116.8 mm with strong evapotranspiration of 2 390 mm. More than 65% of the precipitation occurs from July to September. The wind speed can reach up to 17 m/s in history and may cause a sandstorm(Zhou, Zhao, & Zhang, 2017).

Six field sites were selected on the fluvial fans along the southwestern belt transect from Hanshuishi Hill to the agriculture zone (Figure 1b and 1c). All study sites are covered with desert pavements. Site Hillside is located on the hillside (aspect: southeastern; slopes: <15°), where several small erosion rills appears between hillsides. The surfaces are covered by 36.14%-64.07% of gravels with angular and very-angular shape (Table 1). Vegetation is mainly distributed in the low-lying area (bare ground) or on both sides of the water channels, and mainly dominates the shrubs and annual herbs, such as *Nitraria sphaerocarpa*, *Reaumuria songarica*, *Eragrostis pilosa*, *Setaria viridis*, *Stipa tianschanica* et al (Table 1). The other five sites (Sector 1-5) are located in the sectors of fluvial fans with the mosaic surfaces, which consisted of desert pavement and bare ground. Sometimes the surfaces are eroded by the water channels (Figure 1b) and influenced by agricultural activity to a variable extent. Their surface gravels had variable coverage, changing from 19.48% to 97.63%, and are characterized by sub-angular and angular shape (Table 1). Shrubs are sparsely distributed on the pavement surface, such as *Nitraria sphaerocarpa*, *Reaumuria songarica*. While herbs only grew on the bare ground or below the shrubs, including *Artemisia sieversiana*, *Heteropappus altaicus*, *Eragrostis pilosa*, *Setaria viridis* et al. (Table 1).

2.2. Field investigation and infiltration experiment

2.2.1. Soil properties survey

At each site, ten 50-cm soil pits were dug on the mosaic DP surfaces to measure the soil bulk density, soil moisture content (SMC), particle composition and soil horizon morphology. Soil bulk density was measured using a steel ring via the oven drying method, including topsoil bulk density and subsoil bulk density. Topsoil and subsoil were the 0-5 cm and 5-50-cm depth of soil from the pavement surfaces, respectively. Subsoil was sampled at five levels, including 5-10, 10-20, 20-30, 30-40 and 40-50 cm. Meanwhile, soil sample was collected with sealing bags from the pavement layer and its underlying soil (subsoil) to measure the SMC and particle composition. Subsoil was sampled at seven levels, including 0-3, 3-6, 6-10, 10-15, 15-25, 25-35 and 35-50 cm below the pavement layer. SMC was measured via the oven drying method. Particle composition was determined using the soil sieve method. It was classified by the particle size classes of USDA system: fine earth (≤2 mm), fine gravel (2-5 mm), medium gravel (5-20 mm) and coarse gravel (20-76 mm) (Staff, 2017). These properties of subsoil were calculated by weight method. Soil horizons morphology were diagnosed by the Soil Survey Manual (Staff, 2017), including the soil horizon, horizon/ layer thickness, soil structure of Av horizon (Av structure) and so on.

In addition, a 40-m belt transect was selected at each site to gauge the pavement thickness, gravel size and gravel roundness. Forty small quadrates (10 cm×10 cm) were set at 1-m interval along this transect. Pavement thickness was measured by a steel ruler within each quadrate. All pavement layer samples were collected and brought back to the laboratory of Linze Station. After grinded and sieved though a 2-mm hold sieve, 200 gravels were selected randomly from treated samples to measure gravel size and gravel roundness. Gravel size was calculated by the geometric mean of the long, medium and short axes of gravel, which was measured by the electronic vernier caliper. Gravel roundness was determined by Power's method (Powers, 1953), who classified the roundness into six levels: very angular (R1), angular (R2), sub-angular (R3), sub-rounded (R4), rounded (R5) and well-rounded (R6).

2.2.2. Vegetation survey

Species and coverage of vegetation were surveyed using quadrat method from October 1 to 7, 2019. At each site, vegetation was investigated by six quadrats (size: 5m×5m). Vegetation coverage (mainly shrub coverage) was also surveyed six times by unmanned aerial vehicle (UAV, Type: Phantom 4 Pro) from September 12 to 13, 2020. Before shooting images, surface control points were selected with the boundary of 25m×25m. Furthermore, these images of UAV were used for identifying the surface mosaics and water channels.

2.2.3. Water infiltration experiment

At each soil pit, water infiltration experiments were carried out on mosaic DP from September 25 to October 7, 2019 (Figure 2a). Water infiltration parameters were determined by a disk infiltrometer (Φ = 17 cm) under the constant pressure of -1 cm H_2O at each experiment. On each site, ten pairs of in-situ infiltration experiments were conducted, including natural pavement layers and scalped pavement layers (Figure 2b). Natural pavement layer is formed by the coevolution of pavements and Av horizon under rain splash erosion and redeposition (Bouza, Valle, & Imbellone, 1993; Bresson & Valentin, 1990). Scalped pavement layer is the surface after pavement layer is wiped. Altogether, sixty pairs of tests were accomplished.

Prior to each test, an undisturbed pavement layer surfaces were achieved by weeding dead branches and fallen leaves (Figure 2c). Moist sand (<2 mm) was placed on the treated surface. The disc infiltrometer filled with water (vol. = 962 mL) was installed on the moist sand layer carefully and quickly to ensure the disc closely contacting with sand layer. Test data was collected by manual reading with 5, 10, 20 or 30 s until the water in the tube was exhausted. Then the infiltration experiment on the scalped pavement surface was conducted following the above steps.

2.3. Computation methods

2.3.1. Calculation of water infiltration parameters

Water infiltration parameters were calculated by the Philip model (Philip, 1957). Figure 2d showed the schematic diagram of estimating these parameters. The soil sorptivity (S, cm/min$^{0.5}$) reflects the effect of soil metric on infiltration. It is estimated by the following Philip equation

$$I(t) = S \cdot t^{1/2} \tag{1}$$

Where I is the cumulative infiltration volume per unit area (cm) and the t is the infiltration time (min).

Initial infiltration rate (i_{int}, cm/min) reflects the water flow rate related to the initial soil moisture at the beginning of infiltration. It often refers to the infiltration rate in the first minute.

Steady- state infiltration rate (i_{sat}, cm/min) reflects the infiltration rate when soil water cannot keep flow down rapidly after the soil pores filled with water. It is determined by the derived from equation (1) as follows

$$i(t) = \frac{1}{2} S \cdot t^{-1/2} \tag{2}$$

Where i(t) is the infiltration rate with time. When the infiltration parameters run over 30 min, the infiltration rate is considered to be stable.

Infiltration time (T) reflects the time consumed by infiltration of the specific water quantity into the soil. In this study, the specific water quantity was defined as the water volume in infiltrometer tube (vol. = 962 mL).

2.3.2. Calculation of gravel coverage

Raw images were clipped into squares (size: 10 cm×10 cm). Gravel coverage was extracted by digital image processing method proposed by Butler, Lane, and Chandler (2001). The specific processing steps are as follows: 1) conducting orthochromatic correction and geometrical calibration; 2) recognizing gravel with naked eyes from a rectified image; 3) segmenting the binary image pixels after image grayness; 4) performing threshold segmentation with Global threshold-iterative Method; 5) counting pixels number of black and white in processed using Matlab (Version 2018b); 6) and estimating gravel coverage based on black pixels and white pixels.

2.3.3. UAV image treatment

Raw images were clipped according to the red bars as the surface control points (25 m×25 m). After processed by the orthochromatic and geometrical calibration, clipped images were interpreted by field investigation and visual discrimination. According to the surface features, pavement surface was divided into mosaic surface (i.e. mosaic DP and Mosaic BG) and water channel. The vegetation was classified as the shrub and non-shrub by supervised classification. All classification operations were conducted in ArcGIS (Version 10.2).

2.4. Statistical analysis

Water infiltration parameters was modelled by Philip model. The significance level of modelling results were assessed by two-tailed significance test. The fit strength of results was evaluated by the coefficient of determination (R^2_{adj}) which changed from 0 to 1. The R^2_{adj} is closer to 1, the modelling result **is** better. Kolmogorov- Smirnov test was used to examine the normality of raw data. The differences of soil properties and infiltration parameters at six sites was tested by ANOVA analysis. If passing the homogeneity test, LSD method was adopted for multiple comparisons; otherwise Games-Howell method was used. The relationship between soil properties and infiltration parameters was detected by Pearson correlation. All above statistical analyses were conducted with IBM SPSS Statistics (Version 22.0).

3 | RESULTS

3.1. Soil properties of mosaic DP

3.1.1. Properties of pavement layers

Desert pavements cover the entire fluvial fan surfaces. The physical properties of pavement layer on mosaic DP surface reflected the variance of near-surface characteristics shown in Table 1-2 and Figure 3. Pavement thickness averaged 0.58 cm with a range of 0.10- 2.33 cm. The thickness on the hillside was significantly higher than that in the sectors of fans. Pavement layers of sectors 2-5 were 0.39, 0.53, 0.54, 0.61 and 0.44 cm thick, respectively. Surface gravel coverage averaged 52.94% and ranged from 19.48% to 97.63%. The maximum and minimum of mean values were 76.58% in Sector 1 and 38.44% in Sector 4, respectively. The pavement layer was mainly composed of fine earth (56.94%), followed by medium gravel and fine gravel (fine gravel: 16.48%; medium gravel: 23.97%). Except for fine earth and fine gravel, no significance was found in medium gravel and coarse gravel between both study sites. Gravel size averaged 4.56 mm with a maximum of 31.69 mm in Sector 3 and a minimum of 1.70 in Sector 2. However, gravel size between both sites had no significant difference. Pavement layer had an extremely low SMC with a mean of 0.30 %, and changed from 0.05% to 1.29%. No significance of SMC was detected between both sites on fluvial fans.

3.1.2. Properties of soil profiles

Horizon morphology and soil characteristics are conductive to understand the development and hydrological function of desert pavement. In particular, the hydraulic properties of Av horizon are the critical factor to controlling surface water cycle (Michael H. Young et al., 2004). The horizon morphology and soil properties on mosaic DP were shown in Table 1 and Table 2, and the typical soil profile was presented in Figure 4. Over the fluvial fans, Av horizon was found below the pavement layer and dominated by the prismatic and platy structure. Av horizon averaged 9.89 cm thick, and was significantly different between the hillside and sectors of fans. On the hillside, Av thickness averaged 6.04 cm and was significantly thinner than that in the sectors of fans, where the average Av thickness was 11.64 (Sector 1), 9.97 (Sector 2), 10.03 (Sector 3), 10.93 (Sector 4) and 10.72 cm (Sector 5), respectively. Below the Av horizons, Bk, Btk or C horizons can be found. C horizon mainly appeared on the hillside, but Bk horizons mainly presented the soil profile of sectors, mingling with the Btk horizons.

Topsoil bulk density averaged 1.67 g/cm^3 with varying from 1.21 g/cm^3 to 2.12 g/cm^3. Its maximum and minimum were 1.80 g/cm^3 in Sector 5 and 1.48 g/cm^3 on the hillside, respectively. In particular, topsoil bulk density on the Hillside was lighter than that in sectors. In contrast, subsoil bulk density was less than that in topsoil. It averaged 1.63 g/cm^3 and ranged from 1.31 g/cm^3 to 1.83 g/cm^3. Similarly, the maximum and minimum were also in Sector 5 (1.72 g/cm^3) and on the hillside (1.54 g/cm^3). Subsoil bulk density on the hillside was significantly lighter than that in sectors. In contrast with pavement layers, subsoil mainly consisted of fine earth (77.57%), followed by fine gravel (13.91%) and coarse gravel (7.66%). The fine earth was higher in subsoil than in pavement layers. Compared hillside, fine earth and fine gravel in sectors were significantly higher and lower, respectively. Whereas no significant differences were found in medium gravel and coarse gravel between them. The SMC of subsoil averaged 2.09 % and changed from 0.98% to 7.48%. No significant difference in SMC was found between both study sites.

3.2. Infiltration and its influence factors on mosaic DP surface

3.2.1. Variations of infiltration parameters

According to the simulated results of Philip model, the range of R^2_{adj} ranged between 0.897 and 1.000. The results indicated Philip Model well fitted the accumulative infiltration volume and infiltration time. The infiltration parameters were estimated by Philip Model and were analyzed by mathematical statistics and ANOVA (Figure 5). For pavement layers, the S, i_{int}, i_{sat} and T averaged 1.30 cm/min$^{-0.5}$, 5.03 cm/min, 0.23 cm/min, and 12.76 min, respectively. Their coefficients of variation were 22.47%, 22.46%, 22.43% and 66.93%, respectively. In contrast, for scalped pavement layers, the mean S, i_{int} and i_{sat} increased significantly by 0.75 cm/min$^{-0.5}$,2.90 cm/min and 0.13 cm/min, respectively, while the T was shortened significantly by 7.42 min (S: $F_{1,118}$=92.81, p<0.001; i_{int}: $F_{1, 118}$= 92.86, p< 0.001; i_{sat}: $F_{1,118}$=92.63, p<0.001). The coefficients of variation of S, i_{int} and i_{sat} increased lightly (S: 25.70%, i_{int}: 25.70%, i_{sat}: 25.60%), but the coefficient of variation of T decreased (60.98%). For pavement layer, the S, i_{int} and i_{sat} on the hillside were less than these in the sectors, where these three parameters decreased toward the agriculture zone. Whereas the T presented the reverse trend. In contrast, for scalped pavement layer, the S, i_{int}, i_{sat} and T had the same sites for maximum and minimum on average values. However, the trends of these parameters toward the agriculture zone were not found. The results indicated that the variation of water infiltration was different between the natural and scalped pavement layer.

3.2.2. Factors influencing the variation of infiltration parameters

Table 3 showed the correlation between soil properties and infiltration parameters by Pearson correlation analysis. No significant differences were found between infiltration parameters and gravel size, SMC, bulk density, medium gravel and coarse gravel. In contrast, the S, i_{int}, and i_{sat} were negatively related to the pavement layer thickness and fine gravel, and positively to the Av thickness, gravel coverage and fine earth. While the T was positively related to pavement layer thickness and fine gravel, and negative to the Av thickness and fine earth, but not significantly differed from gravel coverage. The results indicated that the gravel size, SMC, bulk density, medium and coarse gravel were not the limited factors for controlling water infiltration, and the pavement layer thickness, Av thickness, gravel coverage, fine earth and fine gravel played a vital role in surface infiltration capacity.

3.3. Surface mosaics and vegetation distribution

Figure 6 reflected the distribution of surface mosaics and vegetation, and Table 4 showed the responding statistical results. Mosaic DP occupied the largest area (60.86%), followed by mosaic BG (37.56%). Their relative area ranged from 53.30% to 75.14% and from 23.42% to 46.70%, respectively. While the area of the water channel was relatively smaller, only 1.57%. Vegetation coverage averaged 35.05%. Their maximum and minimum were 42.70% in sector 1 and 25.38% in sector 5, respectively. Shrub coverage averaged 5.48% with a maximum and minimum of 8.19% in sector 3 and 4.08% on the hillside, respectively. For mosaic DP, vegetation coverage averaged 2.47% changing from 2.01% to 3.21%. For mosaic BG, shrub coverage was the highest (average 10.88%) and varied from 5.74% to 12.87%. Whereas, for water channels, shrub coverage was only 2.13% changing from 0% to 3.72%. In contrast, herb coverage averaged 29.58%. The maximum and minimum of herbs were 35.55% in sector 1 and 18.47% in sector 5, respectively. Herbs were mainly distributed in mosaic DP, and little below the shrubs or on the bed of water channels.

4 | DISCUSSION

4.1. Variance of mosaic desert pavements

Desert pavements coevolve with Av horizon from late Holocene to present (Rossi, Kendrick, & Graham, 2019; Wells, McFadden, Poths, & Olinger, 1995). Similarly to other areas, pavement layer overlays the Av horizon, where the B horizon or C horizon often deposits below Av horizon (Dietze et al., 2016; Knight & Zerboni, 2018). Wood et al. (2005) considered that thickness of pavement layer and Av horizon can vary with surface mosaic types. However, our finding indicated that both thickness were related to the landform. For instance, compared with sectors of fluvial fans, the pavement layer is thicker but the Av horizon is thinner on the hillside (Table 2 and Figure 4). Brown and Dunkerley (1996) indicated the Av horizon becomes thicker toward the foot of the hillslopes, but we investigated that the Av horizon is thicker than the whole hillslopes. We also illustrated that fine earth and bulk density of soil layer on the hillside are less than these in the sectors, but no significant differences in SMC, gravel coverage and surface gravel size (in pavement layer) are found between both study sites. Therefore, mosaic DP can vary with pavement thickness, Av thickness, particle composition and bulk density, rather than SMC, gravel coverage and surface gravel size.

Furthermore, the fine earth in pavement layer was higher than that in its subsoil in the sector of fans except for hillside. As C horizon is rich in gravels, the fine earth in the subsoil on the hillside is less than that in the sectors (Table 2). We noticed that bulk density in topsoil was not always higher than that in subsoil, which depends on the soil horizons or layers. For instance, although Av horizon had a prismatic and platy structure with plenty of pore, Av thickness significantly increased bulk density (Table 3) because of more silt and clay content in Av horizon (Moharana & Raja, 2016). Other layers (i.e. pavement layer, Btk horizon and C horizon) also have unique soil components with the different bulk density (Staff, 2017). In addition, we also found that the SMC on the hillside is higher than that in the sectors of fans. Although soil water is driven upward by evapotranspiration (Hamerlynck et al., 2002), it is also constrained by the soil layers, such as pavement layer (Kaseke et al., 2012). It can be concluded that soil horizons or layers are significant for determining the soil properties. We suggest that studying pavement landscape should consider soil profile morphology.

4.2. Infiltration process and its influencing factors

Pavement layer is a first obstacle layer to reduce rainfall into subsoil. Infiltration data on mosaic DP showed that water infiltration experienced three stages: rapid absorption by soil matrix (S: 1.30 cm/min$^{-0.5}$), rapid infiltration (i_{int}: 5.03 cm/min) and low-stable infiltration (i_{sat}: 0.23

cm/min). The infiltration processes are similar to soil crusts, such as physical soil crusts, biological soil crusts, and salt soil crust (Yang et al., 2016). We found that the pavement layer can reduce water infiltration. Meadows et al. (2008) indicated that the i_{sat} on desert pavement are 0.45 mm/min, 0.44 mm/min, 0.45 mm/min and 5.42 mm/min at the surface age of Qf2 (10-25 ka), Qf3 (50-25 ka), Qf5 (8-14 ka) and Qf6 (4 ka), respectively. In our study, the i_{sat} is relatively lower on the mosaic DP, and even lower (i_{sat}: 0.35 cm/min) when the pavement layer was scalped. This is probably caused by the properties of pavement layer and Av horizon. In contrast with soil crusts, water infiltration of mosaic DP was slightly lower, such cyanobacteria crusts (0.20-0.24 cm/min) and moss crusts (1.84-2.15 mm/min) (Wang, Zhang, Liu, Geng, & Wang, 2017; Yang et al., 2016). The results indicated that pavement layer can effectively inhibit water infiltration so that generating more runoff.

The water infiltration process of desert pavements is very complex and is affected by multiple factors (Meadows et al., 2008). Significant relationships were found between water infiltration and pavement properties, such as pavement thickness (+), gravel coverage (-), fine earth (-) and fine gravel (+). At first stage, pavement surfaces are wetted rapidly due to its high metric potential caused by the dry soil (Table 2). The soil metric potential is closely related to soil texture (Askari, Tanaka, Setiawan, & Saptomo, 2008), which is defined as "the weight proportion of the separates for particles less than 2 mm in diameter as determined from a laboratory particle-size distribution" (Staff, 2017). Therefore, fine earth content in pavement layer determines the matrix potential. Under the considerable soil moisture, more fine earth has higher potential, which results in stronger soil absorption. While gravels, mainly a large amount of fine gravel, are opposite. With the pavement thickness, fine earth content decreases and gravel increases (Table 3), thus weakening the soil matric potential and resulting in lower soil absorption. However, pavement thicken may not increase gravel coverage due to the limited surface area. So gravel coverage may be a superficial phenomenon. In second and third stage, rainfall only passes through the fine earth into subsoil because of the impermeability of gravel. Therefore, more fine earth and less gravels promote water infiltration on the pavement layer (Table 3). When the pavements become thicker, less fine earth provides the narrow and long seepage channel to reduce water infiltration. While more gravels can be embedded into the interior pavement layer to keep its stable, because the amount of gravels remaining on the surface is finite. As a result, the effect of gravel coverage on the infiltration is related to the gravels within the interior pavement layer. Relative research has explained that the relationship between gravel coverage and water infiltration depended on the degree of gravel embedding in the fine earth (Abrahams & Parsons, 1991; Poesen et al., 1990). Therefore, the pavement layer inhibits water infiltration, thus prolonging the infiltration time to convey excess rainfall into other focus areas. Although the uniform and small gravels within the pavement layer decrease water infiltration (Hamerlynck et al., 2002), this result is not presented in our study. Furthermore, the truth "the lower the initial water content is, the faster the initial infiltration rate is" in soil physics is also not confirmed in this study. The above phenomena may be caused by no significant difference in gravel size and SMC on the fluvial fans (Table 2 and Figure 3).

In contrast with pavement layer, Av horizon is rich in fine earth (Adelsberger et al., 2013). The thicker Av horizon can reduce water infiltration, but significant differences of the i_{sat} values are not found in older pavement (Meadows et al., 2008). Meadows et al. (2008) interpreted the phenomenon as the transformation from matrix flow to preferential flow with the age of desert pavement. However, we found that the Av horizon has a positive effect on water infiltration in this study. The reason probably arises from the difference of water infiltration capacity between pavement layer and Av horizons. Because water infiltration in pavement layer is lower than that in Av horizon (Figure 5), water is rapidly absorbed, diffused and infiltrated in the Av horizon.

4.3. Effect of mosaic desert pavement on eco-hydrological process

Desert pavements are considered as a barren landscape with sparse vegetation, which ascribes to the abiotic landform evolution (Musick, 1975; Pietrasiak et al., 2014). However, our field survey data for the fluvial fans of Northern Linze showed that desert pavements have sealed and mosaic surface. In several studies, gravel coverage was used to distinguish the mosaic DP and mosaic BG (Musick, 1975; Wood et al., 2002). Wood et al. (2005) considered that pavement surface where gravel coverage more than 65% is the mosaic DP, otherwise is the mosaic BG in Cima Volcanic field of Mojave Desert. In contrast with Wood's findings, gravel coverage of mosaic DP has a larger range (19.48% -97.63%) in this study. This indicated that the gravel coverage cannot effectively distinguish heterogeneous patches on the pavement surface. As another representation index observed by naked eyes, vegetation is taken into consideration. We found that shrubs in DP are less than those in BG in our study area. The similar description was obtained from the tables of Wood et al. (2005), who investigated that shrub coverage accounts of 0-5% on the mosaic DP and is more than 9% in the mosaic BG. This is probably affected by geographic position and historic climate environment. Therefore, we suggest that gravel coverage and shrubs should be considered together when the surface mosaics are classified.

Desert pavements can reflect the vegetation distribution by soil moisture regimes (Wood et al., 2005). The survey data of vegetation indicated that vegetation mainly grew in the mosaic BG and only a few shrubs distributed in the mosaic DP. The mosaic surface is critical for maintaining the stability of pavement landscape, which can control vegetation distribution by water and salt stresses (Wood et al., 2005). In arid regions, rainfall is a scarce and unpredictable resource. When the occurrence of rainfall, excess rainwater can be delivered from the mosaic DP to the mosaic BG and other focus areas due to the low water infiltration of mosaic DP. In contrast with mosaic DP, mosaic BG has relatively higher infiltration capacity and concave shape (Pietrasiak et al., 2014; Wood et al., 2005). Therefore, a large amount of water is restored in the subsoil of mosaic BG, which provides the necessary conditions for vegetation germination and growth. Therefore, plenty of herbs appear in the mosaic BG after the rainfall. However, under the high evapotranspiration, solute salts with water can migrate up to the topsoil beneath the pavement layer, which constrains the root system growth (Kaseke et al., 2012; Kianian, 2014). In addition, mosaic DP is relatively smooth (Pietrasiak et al., 2014) so that the surface is bad for preserving seed banks. While mosaic BG has a concave shape and remains roots of perennial plants, dead branches and leaves. Therefore, mosaic BG surfaces are available for seed reservoir and vegetation survival. However, once the pavement layer is destroyed, surface hydrologic processes should be varied, thus influencing the vegetation ecology. Fortunately, pavements can be self-healed and recovered, which is important for surface hydrologic cycle (Adelsberger et al., 2013). Therefore, constructing surface mosaic patterns benefits for the stability of pavement landscape.

In summary, this study illustrated that the effects of mosaic DP on water infiltration and vegetation distribution. However, the surface mosaics of pavement landscape are not effectively expressed on the landscape scale due to the lack of high resolution remote sensing image. The eco-hydrological function of mosaics needed to be further studied. Future work should focus on the eco-hydrologic function and evolution of surface mosaics on pavement landscape.

5 | CONCLUSIONS

We conclude that a) desert pavements appear in a mosaic pattern of desert pavement and bare ground. Significant differences in the mosaic DP between hillside and sectors of fans mainly reflect in pavement thickness, Av thickness, soil particle composition and bulk density rather than SMC, gravel coverage and surface gravel size. Soil horizons of mosaic DP is the key factor for the differences of bulk density, particles composition and SMC. b) Pavement layer on mosaic DP surface can reduce water infiltration. When the pavement layer is removed, the S, i_{int} and i_{sat} can increase by 0.75 cm/min$^{-0.5}$, 2.90 cm/min and 0.13 cm/min, respectively and the T is shortened by 5.34 min. Water infiltration capacity on the pavement surface is influenced by pavement thickness, Av thickness, gravel coverage, and fine earth and fine gravel of pavement layer. c) Mosaic DP grows few shrubs, which are also distributed in the mosaic BG with plenty of herbs. The vegetation is sustained by delivering rainfall from mosaic DP to mosaic BG. Therefore, this water self-regulation function on the pavements is available to maintain stability of pavement landscape.

This study deepens the understanding of the eco-hydrologic processes of fluvial fans and supports decision-making for the local management. Further study of eco-hydrologic function of mosaic surfaces is recommended, as these mosaic surfaces display the disparate surface and ecological features.

REFERENCES

Abrahams, A. D., & Parsons, A. J. (1991). Relation between infiltration and stone cover on a semiarid hillslope, southern Arizona. *Journal of Hydrology*, *122*, 49-59. doi:10.1016/0022-1694(91)90171-D

Adelsberger, K. A., Smith, J. R., McPherron, S. P., Dibble, H. L., Olszewski, D. I., Schurmans, U. A., & Chiotti, L. (2013). Desert pavement disturbance and artifact taphonomy: a case ttudy from the Eastern Libyan Plateau, Egypt. *Geoarchaeology an International Journal*, *28*(2), 112-130. doi:10.1002/GEA.21431

Askari, M., Tanaka, T., Setiawan, B. I., & Saptomo, S. K. (2008). Infiltration characteristics of tropical soil based on water retention data. *Journal of Japan Society of Hydrology & Water Resources*, *21*(3), 215-227. doi:10.3178/JJSHWR.21.215

Bouza, P., Valle, H. F. D., & Imbellone, P. A. (1993). Micromorphological, physical, and chemical characteristics of soil crust types of the central Patagonia region, Argentina. *Arid Land Research and Management*, *7*(4), 355-368. doi:10.1080/15324989309381368

Bowman, D. (2018). *Principles of alluvial fan morphology*.

Bresson, L. M., & Valentin, C. (1990). Comparative micromorphological study of soil crusting in temperate and arid environments. In (pp. 238-243).

Brown, K. J., & Dunkerley, D. L. (1996). The influence of hillslope gradient, regolith texture, stone size and stone position on the presence of a vesicular layer and related aspects of hillslope hydrologic processes: a case study from the Australian arid zone. *Catena*, *26*, 71-84. doi:10.1016/0341-8162(95)00034-8

Butler, J. B., Lane, S. N., & Chandler, J. H. (2001). Automated extraction of grain-size data from gravel surfaces using digital image processing. *Journal of Hydraulic Research*, *39*(5), 519-529. doi:10.1080/00221686.2001.9628276

Chen, L., Yin, J., Miller, J., & Young, M. (2009). The Role of the Clast Layer of Desert pavement in Rainfall-Runoff Processes. In (pp. 6509-6516).

Dietze, M., Dietze, E., Lomax, J., Fuchs, M., Kleber, A., & Wells, S. G. (2016). Environmental history recorded in aeolian deposits under stone pavements, Mojave Desert, USA. *Quaternary Research*, *85*(1), 4-16. doi:10.1016/J.YQRES.2015.11.007

Goudie, A. S. (2013). *Arid and Semi-Arid Geomorphology*.

Haff, P. K. (2001). Desert Pavement: An Environmental Canary? *Journal of Geology*, *109*(5), 661-668. doi:10.1086/321960

Hamerlynck, E. P., McAuliffe, J. R., McDonald, E. V., & Smith, S. D. (2002). Ecological responses of two Mojave Desert shrubs to soil horizon development and soil water dynamics. *Ecology*, *83*(3), 768-779. doi:10.1890/0012-9658(2002)083[0768:EROTMD]2.0.CO;2

Hupy, J. P. (2004). Influence of vegetation cover and crust type on wind-blown sediment in a semi-arid climate. *Journal of Arid Environments*, *58*(2), 167-179. doi:10.1016/S0140-1963(03)00129-0

Iverson, R. M. (1979). *Processes of accelerated pluvial erosion on desert hillslopes modified by vehicular traffic*.

Kaseke, K. F., Mills, A. J., Henschel, J., Seely, M. K., Esler, K., & Brown, R. (2012). The effects of desert pavements (gravel mulch) on soil micro-hydrology. *Pure and Applied Geophysics*, *169*(5), 873-880. doi:10.1007/S00024-011-0367-2

Kianian, M. k. (2014). Studying surface properties of desert pavements and their relation to soil properties and plant growth in Hajaligholi playa, Iran. *Arabian Journal of Geosciences*, *7*(4), 1457-1461. doi:10.1007/S12517-012-0738-8

Knight, J., & Zerboni, A. (2018). Formation of desert pavements and the interpretation of lithic-strewn landscapes of the central Sahara. *Journal of Arid Environments*, *153*, 39-51. doi:10.1016/J.JARIDENV.2018.01.007

McDonald, E. V., Pierson, F. B., Flerchinger, G. N., & McFadden, L. D. (1996). Application of a soil-water balance model to evaluate the influence of Holocene climate change on calcic soils, Mojave Desert, California, U.S.A. *Geoderma*, *74*, 167-192. doi:10.1016/S0016-7061(96)00070-5

Meadows, D. G., Young, M. H., & McDonald, E. V. (2008). Influence of relative surface age on hydraulic properties and infiltration on soils associated with desert pavements. *Catena*, *72*(1), 169-178. doi:10.1016/J.CATENA.2007.05.009

Moharana, P. C., & Raja, P. (2016). Distribution, forms and spatial variability of desert pavements in arid western Rajasthan. *Journal of the Geological Society of India*, *87*(4), 401-410. doi:10.1007/S12594-016-0408-7

Musick, H. B. (1975). Barrenness of Desert Pavement in Yuma County, Arizona. In (Vol. 10).

Philip, J. R. (1957). THE THEORY OF INFILTRATION: 4. SORPTIVITY AND ALGEBRAIC INFILTRATION EQUATIONS. *Soil Science*, *84*(3), 257-264. doi:10.1097/00010694-195709000-00010

Pietrasiak, N., Drenovsky, R. E., Santiago, L. S., & Graham, R. C. (2014). Biogeomorphology of a Mojave Desert landscape — Configurations and feedbacks of abiotic and biotic land surfaces during landform evolution. *Geomorphology*, *206*, 23-36. doi:10.1016/J.GEOMORPH.2013.09.015

Poesen, J., Ingelmo-Sanchez, F., & Mücher, H. (1990). The hydrological response of soil surfaces to rainfall as affected by cover and position of rock fragments in the top layer. *Earth Surface Processes and Landforms*, *15*(7), 653-671. doi:10.1002/ESP.3290150707

Powers, M. C. (1953). A New Roundness Scale for Sedimentary Particles. *Journal of Sedimentary Research*, *23*(2), 117-119. doi:10.1306/D4269567-2B26-11D7-8648000102C1865D

Rossi, A. M., Kendrick, K. J., & Graham, R. C. (2019). Pedogenic evolution on the arid Bishop Creek moraines, eastern Sierra Nevada, California. *Catena*, *183*. doi:10.1016/j.catena.2019.104222

Rostagno, C. M., & Degorgue, G. (2011). Desert pavements as indicators of soil erosion on aridic soils in north-east Patagonia (Argentina). *Geomorphology*, *134*(3), 224-231. doi:10.1016/J.GEOMORPH.2011.06.031

Staff, S. S. D. (2017). *Soil survey manual*. Washington, D.C.: United States Department of Agriculture.

Wang, H., Zhang, G., Liu, F., Geng, R., & Wang, L. (2017). Effects of biological crust coverage on soil hydraulic properties for the Loess Plateau of China. *Hydrological Processes*, *31*(19), 3396-3406. doi:10.1002/HYP.11263

Wells, S. G., McFadden, L. D., Poths, J., & Olinger, C. T. (1995). COSMOGENIC HE-3 SURFACE-EXPOSURE DATING OF STONE PAVEMENTS - IMPLICATIONS FOR LANDSCAPE EVOLUTION IN DESERTS. *Geology*, *23*(7), 613-616. doi:10.1130/0091-7613(1995)023<0613:chsedo>2.3.co;2

Wood, Y. A., Graham, R. C., & Wells, S. G. (2002). Surface mosaic map unit development for a desert pavement surface. *Journal of Arid Environments*, *52*(3), 305-317. doi:10.1006/JARE.2002.1006

Wood, Y. A., Graham, R. C., & Wells, S. G. (2005). Surface control of desert pavement pedologic process and landscape function, Cima Volcanic field, Mojave Desert, California. *Catena*, *59*(2), 205-230. doi:10.1016/J.CATENA.2004.06.001

Yang, J. L., Zhang, G. L., Yang, F., Yang, R. M., Yi, C., Li, D. C., . . . Liu, F. (2016). Controlling effects of surface crusts on water infiltration in an arid desert area of Northwest China. *Journal of Soils and Sediments*, *16*(10), 2408-2418. doi:10.1007/S11368-016-1436-Z

Young, M. H. (2003). Infiltration Through Desert Pavements, Mojave Desert, CA, USA. In.

Young, M. H., McDonald, E. V., Caldwell, T., Benner, S. G., & Meadows, D. G. (2004). Hydraulic Properties of a Desert Soil Chronosequence in the Mojave Desert, USA. *Vadose Zone J.*, *3*(3), 956-963. doi:10.2113/3.3.956

Zhou, H., Zhao, W. Z., & Zhang, G. F. (2017). Varying water utilization of Haloxylon ammodendron plantations in a desert−oasis ecotone. *Hydrological Processes*, *31*(4), 825-835. doi:10.1002/HYP.11060