Published September 27, 2018

Special Section: UZIG Research: Land-Use and Climate Change Impacts on Vadose Zone Processes

Ecohydrologic Changes Caused by Hydrologic Disconnection of Ephemeral Stream Channels in Mojave National Preserve, California

Kim S. Perkins,* David M. Miller, Darren R. Sandquist, Miguel Macias, and Aimee Roach

Core Ideas

- Emplacement of infrastructure has modified ecohydrology in the Mojave Desert.
- Channels with no upslope water sources have altered infiltration properties.
- Microbial and vegetation assemblages have evolved with hydrologic changes.
- Deeper rooting plants are more abundant where streams can flow ephemerally.

Emplacement of highways and railroads has altered natural hydrologic systems by influencing surface-water flow paths and biotic communities in Mojave National Preserve. Infiltration experiments were conducted along active and abandoned channels to evaluate changes in hydrology and related effects on plant water availability and use. Simulated rainfall infiltration experiments with vegetation monitoring were conducted along an active channel upslope and a comparable abandoned channel downslope of the transportation corridor. We also conducted 90 single-ring, ponded infiltration experiments in adjacent channels to evaluate field-saturated hydraulic conductivity and particle size distributions. The abandoned channels are still morphologically evident but are disconnected from runoff sources at higher elevations. Infiltration test results show that water infiltrates twice as fast in the active channels. Excavation showed weak soil development with fewer plant roots beneath the abandoned channel. Scanning electron microscopy of surface samples showed the presence of cyanobacteria only in abandoned channels. Plants up to 3 m away from both channels showed physiological responses to channel water applied in a simulated pulse of rain. The response was short lived and less pronounced for plants adjacent to the abandoned channel, whereas those adjacent to the active channel showed responses up to 2 mo after the pulse. These responses may explain observed lower plant densities and fewer deep-rooted species along abandoned channels compared with active channels. We infer that the deeper rooting plants are more abundant where they are able to take advantage of the increased soil-water storage resulting from greater infiltration and flow frequency in active stream channels.

Abbreviations: BSC, biological soil crust; SEM, scanning electron microscope.

K.S. Perkins and D.M. Miller, US Geological Survey, 345 Middlefield Rd., MS-421, Menlo Park, CA 94025; D.R. Sandquist and M. Macias, Dep. of Biological Science, California State Univ.–Fullerton, 800 N. State College Blvd., Fullerton, CA 92834; A. Roach, Environmental Studies Program, California State Univ.–Fullerton, CA 92834. *Corresponding author (kperkins@usgs.gov).

Received 28 Jan. 2018.
Accepted 10 Aug. 2018.

Citation: Perkins, K.S., D.M. Miller, D.R. Sandquist, M. Macias, and A. Roach. 2018. Ecohydrologic Changes caused by hydrologic disconnection of ephemeral stream channels in Mojave National Preserve, California. Vadose Zone J. 17:180022. doi:10.2136/vzj2018.01.0022

In many desert environments, alluvial fans with complex hydrologic networks of ephemeral stream channels are common. These channels, which comprise a small fraction of the areal landscape, carry most of the runoff from higher elevations and have higher infiltration capacity than surrounding interfluvial areas (Nimmo et al., 2009). They are therefore a critically important influence on biotic communities and processes (Schwinning et al., 2011). Desert plants use different strategies to survive in water-limited environments, with some having the ability to remain dormant for long periods (Hamerlynck et al., 2002; Lombardini, 2006). Previous studies have shown that plants are more abundant along stream margins than in the interfluvial areas between channels (Schwinning et al., 2011) and that biological soil crusts are more abundant in interfluvial areas (Belnap et al., 2014). In Mojave National Preserve (Fig. 1), construction of a railroad and an adjacent levee about 100 yr ago has left many small ephemeral stream channels abandoned from their upstream water sources as water is diverted into culverts spaced hundreds of meters apart (Fig. 2). This has impacted plant densities and species distributions (Schwinning et al., 2011) in the water-deprived areas down fan.

Biological soil crusts (BSCs) play an important and sometimes complex role in arid ecosystems. Biological soil crusts form from the interaction of bacteria, algae, fungi, lichen, and other organisms with soil particles. The organisms and polysaccharide material that they secrete causes soil particles to adhere, creating a crust at the soil surface (Belnap, 2006).

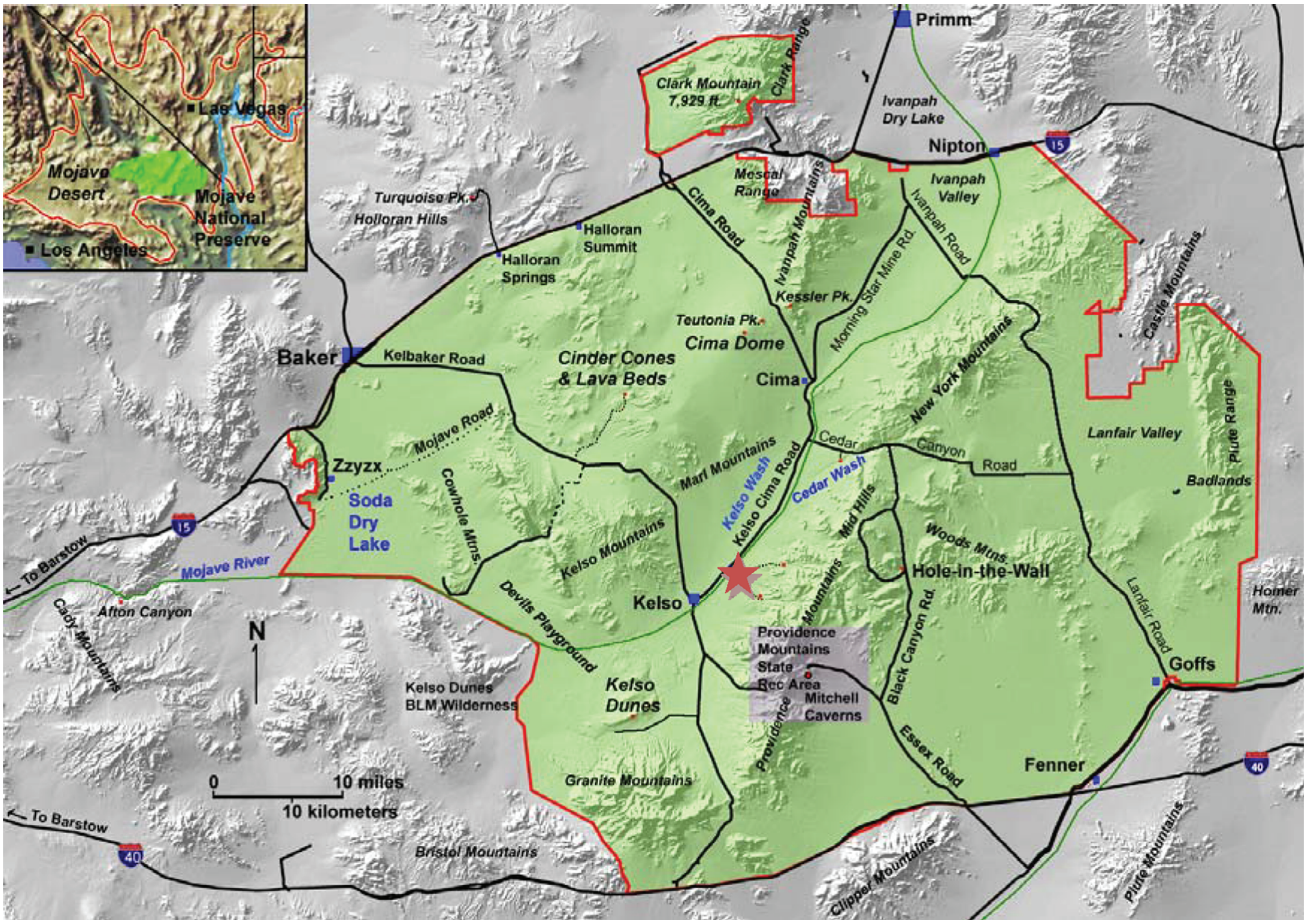

Fig. 1. Map of the Mojave National Preserve. The red star represents the approximate location of the infiltration measurements (35°3′11″ N, 116°4′46″ W).

Cyanobacteria form smooth crusts and are photosynthesizing, which enables them to initiate the succession of BSCs by stabilizing and adding C to the soil surface (Williams et al., 2012). Much has been reported on the role of biological soil crusts and their importance in N_2 fixation, soil C content (Billings et al., 2003), nutrient cycling, energy flow (Belnap, 2003), and soil fertility (Thompson et al., 2005), but studies focusing on near-surface hydrology have shown conflicting results. Some studies have shown decreasing infiltration with the presence of BSCs (Eldridge et al., 2000; Yair, 1990) and others have shown that infiltration and soil moisture increases (Eldridge and Rosentreter, 2003; Malam Issa et al., 2009).

The main purpose of this study was to identify ecohydrologic changes resulting from anthropogenic landscape modification in an arid setting. Contributors to these changes include, but are not limited to, reduced water inputs, reductions in infiltration due to development of BSCs, and changes in soil texture over time with aeolian input of fine material. We focused on channels because they carry a significant amount of runoff down the alluvial fan complex, which concentrates water and leads to deeper infiltration that can be utilized by plants over a longer time than shallower surface infiltration that commonly occurs with areal rainfall. As urban development in fragile arid ecosystems continues, we want to understand how these anthropogenically induced hydrologic changes relate to habitat suitability and overall ecosystem health and function because many desert animal species rely on soil moisture and the protection provided by vegetation.

Study Area and Field Measurements

The field site is located at 750 to 800 m asl within the Mojave National Preserve about 6 km northeast of Kelso Depot on the Globe Fan unit that lies along the west side of the Providence Mountains (Fig. 1). The Globe Fan source area is primarily granite and gneiss (Miller et al., 2009). Stream channels are fringed primarily by *Larrea tridentata* (DC.) Coville (creosote bush) and *Ambrosia dumosa* (A. Gray) Payne (white bursage). Experimental locations for sprinkling infiltration were chosen at two similarly sized (50–75 cm wide with 5–10-cm bank height) ephemeral stream channels (Fig. 2) with 1 to 2% slopes—one upslope of the railroad with a channel that is active during storm events and one downslope with a channel that has been cut off from upslope runoff. The Union Pacific Railroad was built in 1905

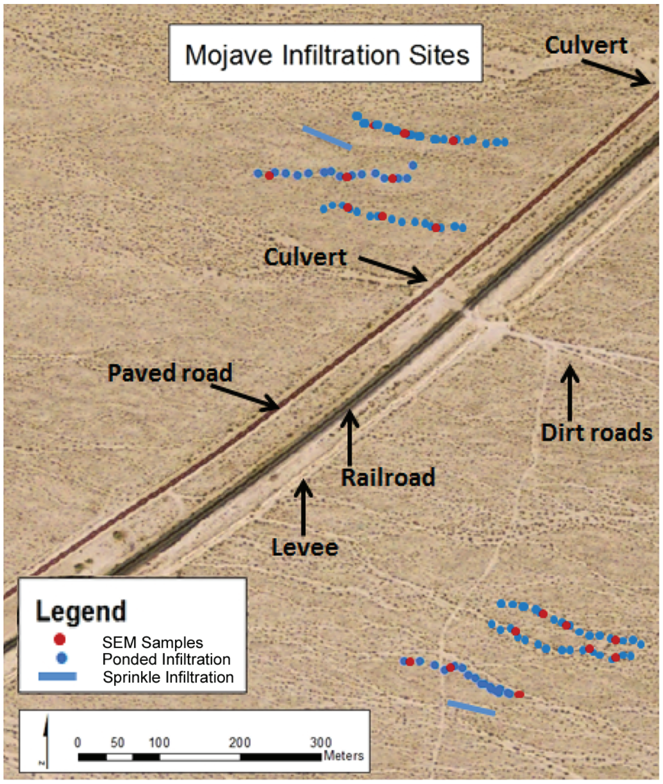

Fig. 2. Location of relevant landscape features. Infiltration transects are indicated by blue lines (sprinkling infiltration) and blue dots (ponded infiltration). Scanning electron microscope (SEM) sample collection sites are indicated by red dots.

with levees constructed to divert runoff into culverts placed every 300 to 500 m (Fig. 2). Channels above the railroad receive flow from higher elevation sources during rainfall events. Most of the channels below the railroad have been disconnected from their major runoff sources as water is diverted into the culverts, creating fewer, larger, active channels that form distributary channels farther down fan. The abandoned channels below the railroad are morphologically evident but presumably have not flowed with contributions other than local runoff in >100 yr.

In both channels, we simulated rain-generated channel flow by irrigating a 30-m reach with the water-volume equivalent of an approximately 20-mm rainfall event over about 100 min. The 20-mm amount was chosen to represent stream flow plus a local rain event that would infiltrate an estimated 50 cm into the soil, based on a 1-m wetted channel width and 20% porosity. That depth was assumed to be well within the rooting zone, and the water input is about 50% of the mean annual summer rainfall in this region. On Days 3, 16, 34, and 61 following the pulse, we measured plant predawn water potential (ψ_{pd}) on 10 creosote bush plants within 5 m of each channel. Predawn water potential is a physiological measure of plant water status as influenced by plant-available soil water. Pre-dawn stem xylem water potential was measured in the field with a Scholander-type pressure chamber (Model 1000, PMS Instrument Co.). Two or three measurements were made per plant between the hours of 2:30 and 4:30 AM, Pacific Daylight Standard Time (PDT). Stems containing live leaves were cut, immediately placed into a plastic bag, and the bag was sealed to avoid desiccation of the cut branch prior to measuring with the pressure chamber. All samples were measured within 5 min of being cut. Water potential values for creosote bush during annual drought cycles typically fall below −6.0 MPa in summer (Jacobsen et al., 2008), but these values rebound quickly and can approach −1.0 MPa following rain pulses (Newlander et al., 2009). Logistic regression was used to determine distances from the channel (independent variable) at which plants responded to the irrigation pulse based on an observed increase in plant ψ_{pd} values relative to their pre-pulse values (dependent variable). Water potential responses vs. distance from the wash were used to empirically determine a best-fit logistic regression model (KaleidaGraph 4.0, Synergy Software). Each regression model was then entered into ArcMap software. Analyses were done separately for each channel and for each day (3, 16, 34, and 61) after the pulse.

Following the irrigation experiment, we measured field-saturated hydraulic conductivity (K_{fs}) in six different channels (three active and three abandoned) adjacent to the sprinkling experiment channels using the method of Nimmo et al. (2009), which uses a portable, falling-head, small-diameter (∼20 cm), single-ring infiltrometer and an analytical formula to calculate K_{fs} from field infiltration data, to compensate for both variable falling head and subsurface radial spreading that unavoidably occurs with the small ring size. After adding water to the ring, we measured the time to zero water, with measurements repeated until rates became steady. The method allows a large number of measurements to be conducted relatively rapidly and is highly suited for comparative studies (Perkins et al., 2012; Nimmo et al., 2009) at field sites such as this that have very limited accessibility to a water source; all water and supplies must be hand carried. We applied this method at 45 locations in active channels and at 45 locations in abandoned channels (Fig. 2) to evaluate differences in hydrology as related to plant water availability and use. Surface samples (0–2-cm depth) were collected at each infiltration location and analyzed for particle-size distribution using laser diffraction (Coulter Model LS-230) for particles from 0.04 μm to 2 mm. An additional 18 samples were collected from the upper 1 cm of the channel surface for analysis with a scanning electron microscope (SEM) to identify any microbes within the samples.

All perennial shrubs within 3 m of the infiltration transect channels were counted and identified to determine plant densities. Soils within the sprinkling infiltration channels were also excavated to ∼80-cm depth and described, including root counts. Roots were counted where they were cut on a troweled pit wall and were described in groups as a function of depth. Soil horizon boundaries were considered in the depth boundaries. Pit walls averaged 40 cm wide. Roots were classed as fine or woody, the latter being generally wider than 3 mm in diameter and stiff. All root measurements were normalized to the surface area of the pit wall as the density of roots per 10-cm width of wall. In one case, a woody root that was nearly vertical showed in more than one place on a pit wall. It was counted only once and assigned a position at its lowest occurrence.

The statistical significance of differences in K_{fs} and the fine fraction (defined as <50 μm) particle size distributions between the active and abandoned channels was tested using a two-sample *t*-test assuming unequal variance at the 95% confidence level. The null hypothesis proposes that no statistical difference exists. To determine any differences in infiltration attributable to channel type (active or abandoned), a rejection of the null hypothesis, the resulting *P* value must be 0.05 or less.

Results

Visually, the active and abandoned channels are similar in morphology. Differences are limited to evidence for recent streamflow in the active channels, as indicated by strandlines of organic materials and the complete absence of tiny (a few millimeters in size) "buttons" of dark lichen, which appear in low densities on the abandoned channel deposits. The channel deposits are granular with significant open pore space, contain a paucity of clay and silt, and contain poorly sorted sand deposits with weak soil horizonation as shown in Fig. 3. Layers due to different depositional events are clearly visible. The channels are floored by an older soil horizon (Bwk) at about the 60- to 80-cm depth. Creosote bush plants up to 3 m from the active channel and 2.5 m from the abandoned channel had pronounced increases in ψ_{pd} up to 16 d following irrigation pulses (green shading, Fig. 4). The response-by-distance relationship was more strongly step-like for the active channel than for the abandoned channel, indicating a more predictable relationship between plants and active channels (active wash: Day 16 R^2 = 0.924, Day 61 R^2 = 0.844; abandoned wash: Day 16 R^2 = 0.568, Day 61 R^2 = 0.483). This would be expected when water availability (infiltration) is regular, such that plant roots would "camp" in the locations of high water content. Furthermore, the positive

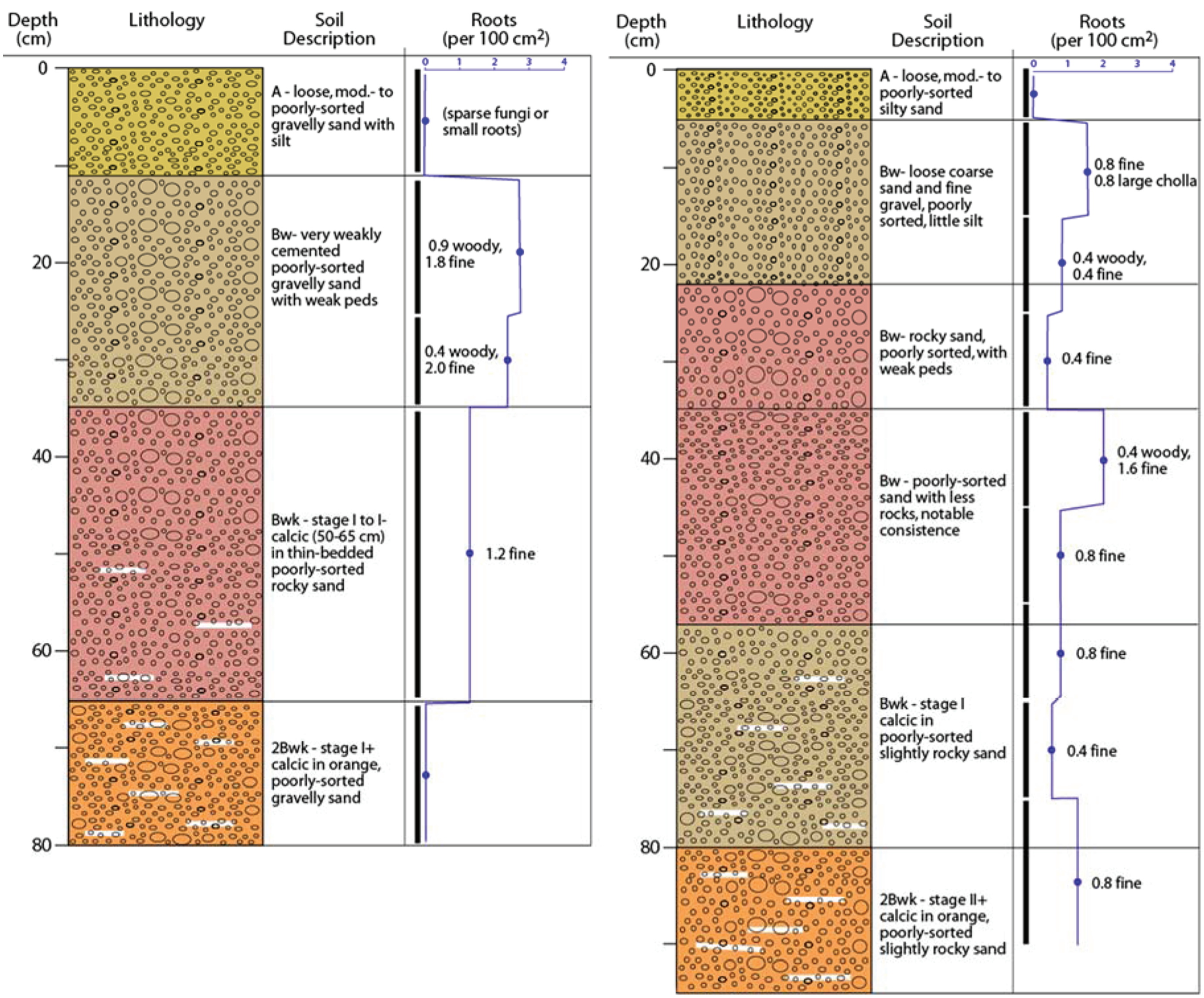

Fig. 3. Soil profiles and root densities for the location of the active channel (left) and abandoned channel (right) used in the sprinkling infiltration experiments.

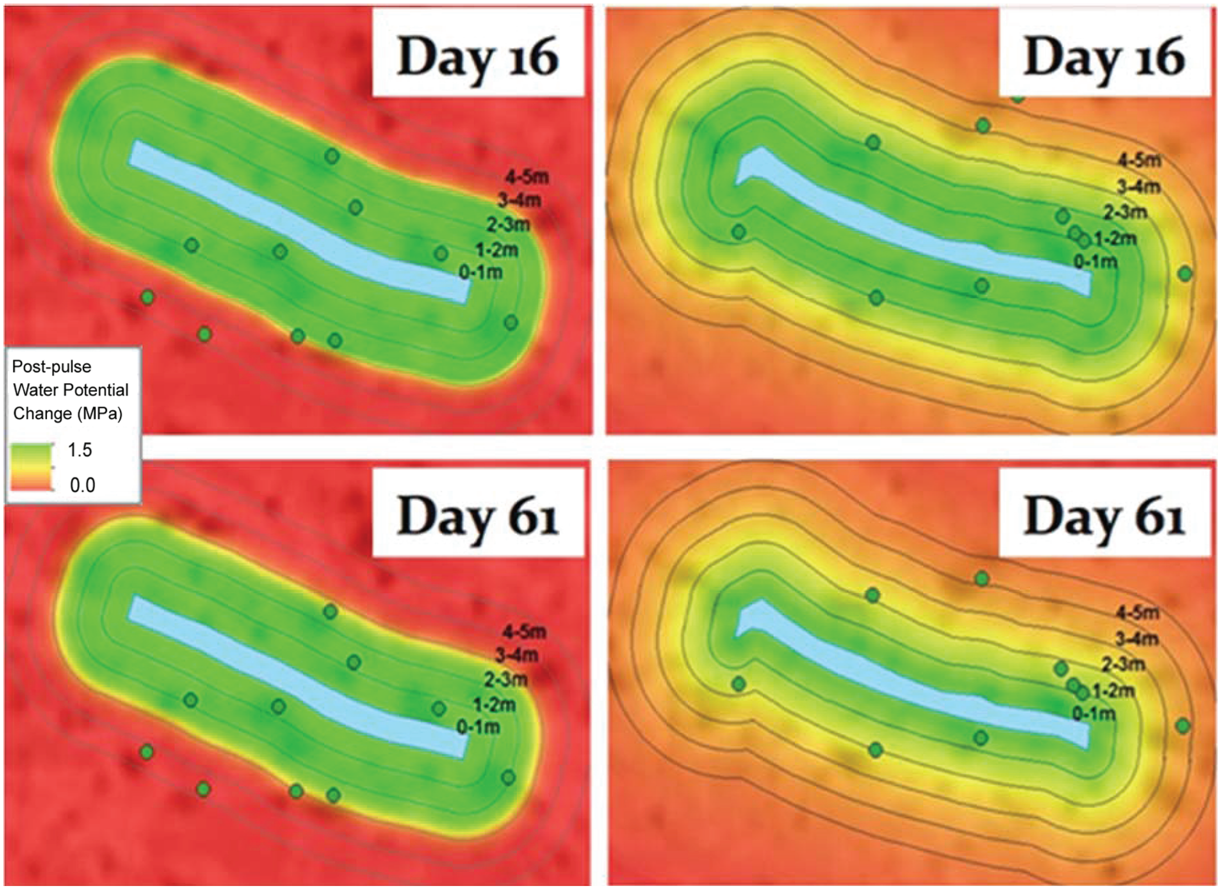

Fig. 4. Water potential responses by *Larrea tridentata* (green dots) to irrigation pulses within active (left) and abandoned (right) channels. Physiological responses to channel irrigation (blue) are color coded from strong response (green) to no response (red) based on logistic regression of predawn water potential (ψ_{pd}) vs. distance from the channel. After 61 d, plants up to ~3 m from the active channel (bottom left) still had detectably higher ψ_{pd} values, whereas only plants <1 m from the abandoned channel (bottom right) showed such advantages after this duration. Weak predictability of plant responses to the pulse is indicated by the greater gradation of color between green and red at the abandoned channels (right). Color shading overlies aerial photos of irrigation sites; dark spots are large plants.

physiological responses of plants up to 3 m from active channels lasted into the second month (61 d) following irrigation, whereas the responses adjacent to abandoned channels attenuated to include only plants <1 m from the channel (Fig. 4).

Comparison of results for the active and abandoned channels for K_{fs} and percentage of fine material (defined as <50 μm) are given in Table 1 along with *P* values from statistical testing.

Table 1. Mean, variance, and statistical significance of differences in field-saturated hydraulic conductivity (K_{fs}) and fines fraction for the active and abandoned channels.

Statistic	Active	Abandoned
K_{fs}, mm/h		
Mean	240	138
Variance	0.29	0.11
P value = 0.032		
Clay and silt, %		
Mean	2.95	2.61
Variance	1.18	1.41
P value = 0.4342		

Differences in K_{fs} are statistically significant at the 95% confidence level, while differences in content of fine material are not significant. Figure 5 shows graphical comparisons of K_{fs}. Particle size distributions (Fig. 6) were similar for the two channel deposits. In contrast, infiltration rates (K_{fs}) were significantly lower on average for the abandoned channel by a factor of 2.

Other measures also indicate differences between active and abandoned channels. Creosote bushes were counted within 3 m of the channels where infiltration tests and sprinkling irrigation experiments were conducted. Plant densities were lower adjacent to abandoned channels, with only 1.5 plants per meter of channel length compared with 3.5 per meter adjacent to active channels. Using root counts integrated along the soil profiles (Fig. 3), root densities (per 100 cm^2) ranged from 10 roots on average beneath active channels to six beneath abandoned channels.

Discussion

Soil development is known to inhibit infiltration in desert soils through accumulation of windblown fines and development

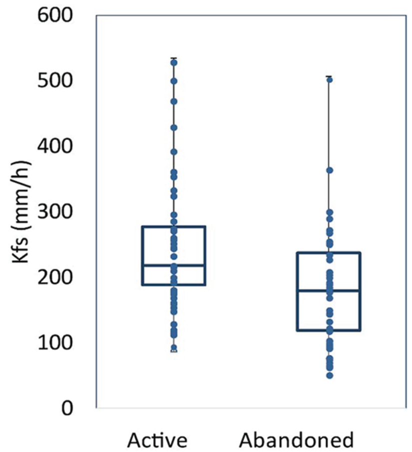

Fig. 5. Box-and-whisker plot comparisons of field-saturated hydraulic conductivity (K_{fs}) (n = 45 for each type). The box indicates the data in the second and third quartiles, with the middle line in the box indicating the median. The top whisker indicates the spread of data in the fourth quartile, and the bottom whisker indicates the spread of data in the first quartile. The dots are the individual data points.

of soil structure (Nimmo et al., 2009). One reason for lower K_{fs} could be the accumulation of windblown fines that may not be flushed down through shallow sands in the abandoned channels as efficiently as they are in the channels that flow seasonally. However, particle size distributions (Fig. 6) for materials in the upper few centimeters were not significantly different above and below the railroad. Percentages of fines were comparable at both locations, with no statistically significant difference (Table 1).

Another explanation for infiltration differences in active and abandoned channels could be the presence of microbes such as cyanobacteria, which are early colonizers that are often difficult to identify in the field (Belnap 2003). Cyanobacteria are evident in SEM images (Fig. 7) for abandoned channels and not evident for active channels. It is possible that cyanobacteria decrease the rate of infiltration in abandoned channels. Cyanobacteria are known to be the first colonizers, followed by lichen, which tend to take from 200 to 1200 yr to colonize in the Mojave Desert (Belnap, 2003). Little is known about colonization for BSCs in abandoned stream channels with respect to species assemblages. Our observation of microbes in abandoned channels indicates that they may be able to colonize in <100 yr.

The relationship between the loss of soil water inputs and the microbial colonization of abandoned stream channels is complex. Biological soil crusts provide many ecosystem services such as soil stabilization, nutrient content, soil energy flux, and physical resistance to the establishment of invasive grasses (Belnap, 2003). However, a reduction in soil water storage may negatively affect some species.

Reduced infiltration due to a lack of regular channel flow may help explain the significantly reduced and less predictable physiological responses of creosote bush plants adjacent to abandoned channels compared with those of active channels. These results suggest that water flow and infiltration in active channels provides a predictable long-term water reserve for plants along active channels—a reserve that is accessed by plants up to 3 m away from the channel. In abandoned channels, flow is unreliable and infiltration capacity is inhibited, thereby precluding an important water resource for *Larrea* and other perennials in these hydrologically altered landscapes.

The *Larrea–Ambrosia* (creosote bush–white bursage) association covers about 70% of the Mojave Desert (Fonteyn and Mahall, 1978). White bursage grows to be about 20 to 60 cm tall, with a hemispheric crown and mainly lateral roots that are up to 70 cm in length (Fonteyn and Mahall, 1978). Creosote grows up to 4 m tall with deep roots extending to 80 cm and secondary lateral roots extending up to 3 m (Fonteyn and Mahall, 1978). Creosote bushes were counted within 3 m of the channels where infiltration tests and irrigation experiments

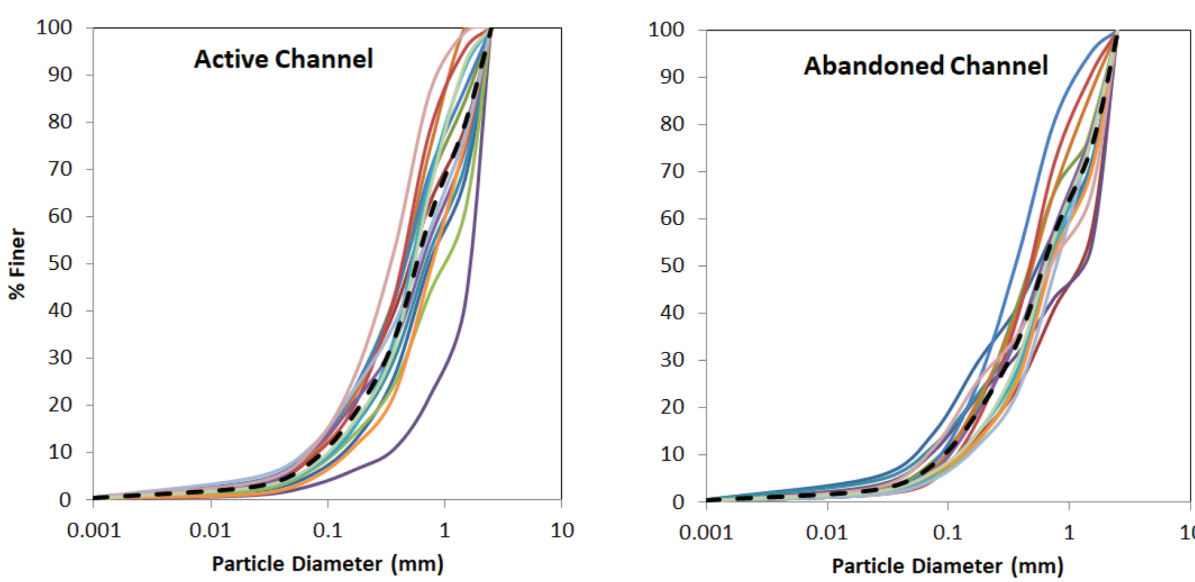

Fig. 6. Example particle size distributions for active and abandoned channels. The black dashed lines indicate the average of all of the data.

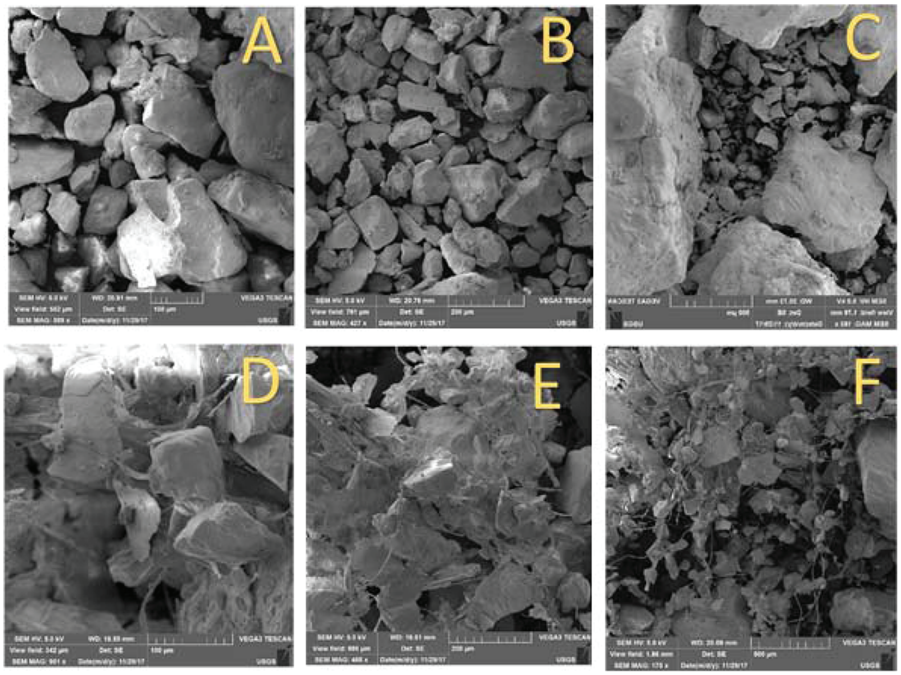

Fig. 7. Example scanning electron micrographs of samples taken from (A,B,C) active channels and (D,E,F) abandoned channels. Filamentous cyanobacteria structures are evident adhering to sediment in the samples from the abandoned channel.

were conducted. Creosote, which is commonly dense along ephemeral channels, is not as prevalent adjacent to abandoned channels, with only 1.5 plants per meter of channel length compared with 3.5 per meter along active channels. White bursage is the dominant species below the railroad, which may be due to the fact that they can avoid extreme drought effects by losing most of their leaves and remaining dormant until favorable conditions return (Ackerman et al., 1980). Creosote, in contrast, retains leaves during drought, relying on residual, deep soil water to provide a minimum transpiration stream. The absence of such water may preclude widespread survival of creosote along abandoned channels.

Small washes and channels create a complex hydrological network across desert bajadas but represent only a small proportion of the bajada's spatial area. Nonetheless, these channels may be the most important geomorphic feature influencing local infiltration and therefore vegetation properties and processes. Plant physiological responses to simulated runoff experiments revealed patterns that, when compounded through time, contribute to changes in vegetation. These findings show that disturbance of small desert washes can lead to vegetation shifts with time, with consequences that are not yet fully realized, likely also affecting burrowing animal species common to arid ecosystems that rely on soil moisture and the protection provided by vegetation. Small desert washes may represent a minor spatial component of the vast landscape, but runoff and higher infiltration rates, coupled with the breadth of their spatial influence on adjacent plants, suggests that these modest geomorphic features may have a disproportionate impact on plant function and community properties in arid ecosystems.

Reduced infiltration can contribute negatively to the water availability for creosote adjacent to abandoned channels despite the adaptive advantages of cyanobacteria growth in the channel deposits. Although we cannot distinguish between the effects of reduced water availability due to reduced stream flow in the abandoned channels vs. reduced infiltration rates, it is likely that both contribute to a reduction of creosote density in flow-deprived areas below the railroad. It is also possible that reduced infiltration results in more shallow water storage, favoring the more shallowly rooted white bursage. Reduced K_{fs} values in abandoned channels is not causally linked to the observed vegetation patterns or function but are instead a consequence of the colonization of cyanobacteria and subsequent crust and soil formation as the abandoned channel surfaces are no longer disturbed by overland flow. Soil development is commonly considered to result from the abandonment of surfaces, after which illuviation of fines gradually alters the profile into distinct soil horizons (McFadden et al., 1989; Pavich and Chadwick, 2004). The soil development dramatically changes infiltration rates and soil moisture balance (e.g., Young et al., 2004) and thus is commonly considered to be the main driver in changing plant species distribution (McAuliffe and McDonald, 1995; Miller et al., 2009). Although little studied, plants may play a role in reducing erosion and stabilizing the surface, allowing soil development to proceed (Miller et al., 2009). Our study suggests that colonization of an abandoned stream deposit by cyanobacteria influences infiltration without a corresponding change in soil characteristics such as an increase in fines, indicating another potential mechanism for driving soil development. Microbial communities may stabilize surfaces sooner than other mechanisms such as development of stone layers, and the reduction of water infiltration will further enhance entrapment of illuvial fines in the shallow soil. Thus, microbial communities may play a large role in initiating and enhancing soil development.

Conclusions

In the Mojave National Preserve, field-saturated hydraulic conductivity in ephemeral channels is reduced as a result of ecohydrologic changes associated with water diversion as a result of emplacement of a railroad about 100 yr ago. Most factors influencing hydrology are similar in active and abandoned channels. However, observations of microbes by SEM analysis within the abandoned channel suggest that early microbial succession is at least partly responsible for the changes in surface hydraulic properties. As colonization continues, probably with other species that are prevalent in the interfluvial areas such as lichen, infiltration rates are predicted to decrease further, enhancing soil development processes and altering plant community composition.

Lower densities of creosote bush along the abandoned channel compared with the active channel imply that this more deeply rooted species no longer preferentially colonizes now-abandoned stream channels to exploit the enhanced water flow such channels would normally provide. At lower densities, these plants may still exploit channel water when available, but the relationship between creosote plants and abandoned channels is much less pronounced than is found with active channels. Instead, the more shallowly rooted and drought-avoiding white bursage dominates these hydrologically altered areas.

Acknowledgments

We would like to express gratitude to people and programs that provided support of this work: The late, great David Bedford, Jane Belnap, John Nimmo, Debra Hughson, Kevin Schmidt, The Recovery and Vulnerability of Desert Ecosystems (RVDE) Project, and the CSUF Department of Biological Science Graduate Student Research Grants-in-Aid program. We also appreciate the thoughtful and insightful reviews provided by Marjorie Schulz (USGS) and two anonymous reviewers. The use of brand names does not imply endorsement by the USGS or the Dep. of the Interior; they are merely there for informative purposes.

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