Semiarid Watershed Response to Low-Tech Porous Rock Check Dams

Mary H. Nichols, Viktor O. Polyakov, Mark A. Nearing, and Mariano Hernandez

Abstract: Rock check dams are used throughout the world to mitigate erosion problems on degraded lands. Many restoration efforts on rangelands in the southwestern United States incorporate such structures; however, their impact on watershed response and channel morphology is not well quantified. In 2008, 37 porous rock structures were built on two small (4.0 and 3.1 ha) instrumented watersheds on an alluvial fan at the base of the Santa Rita Mountains in southern Arizona. Thirty-five years of historical rainfall, runoff, and sediment data are available to compare with 7 years of data collected after check dam construction. In addition, postconstruction measurements of channel geometry and longitudinal channel profiles were compared with preconstruction measurements. The primary impact of the check dams was retention of channel sediment and reduction in channel gradient; however, response varied between the proximal watersheds, with 80% of the check dams on one of the watersheds filled to 100% of their capacity after seven runoff seasons. Precipitation runoff ratios changed after construction, but the change was not persistent after check dams filled to capacity. The contrasting watershed experiences lower sediment yields, and only 20% of the check dams on this watershed was filled to capacity. Within the watersheds, the mean gradient of the channel reach immediately upstream of the structures has been reduced by 35% (from 0.061 to 0.039) and 34% (from 0.071 to 0.047).

Key Words: Check dams, grade stabilization, sediment yield, runoff, channel morphology

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Drylands comprise more than 40% of the global land surface, and it is widely recognized that desertification is a serious environmental threat in both developed and developing countries (Middleton and Thomas, 1997). Many degraded landscapes are characterized by accelerated soil erosion and the associated loss of nutrients and organic matter. In severe cases, gullying and channel incision fundamentally alter surface hydrology by concentrating runoff in channels and limiting the opportunity for runoff to infiltrate and contribute to soil moisture. In arid and semiarid regions, these problems are exacerbated by high-intensity, high-magnitude, and low-frequency rainstorms that lead to high-velocity short-duration flash floods (Coppus and Imeson, 2002; Osborn and Renard, 1988). Low-tech erosion control structures made with natural materials such as rock and brush are used worldwide to mitigate land degradation (Romero-Diaz et al., 2007; Xu, 2005; Nyssen et al., 2004). In southwestern United States, porous rock check dams are being incorporated in restoration efforts through programs such as the Arizona Water Protection Fund (www.azwpf.gov).

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Rock check dams are commonly constructed in low-order headwaters and upper reaches of channel networks where small structures can be effective for grade stabilization and erosion control without the threat of causing damage through catastrophic failure. Rock check dams are typically constructed from either local or purchased rocks that are placed perpendicular to the flow direction. The structures are anchored into the channel bed and banks and may or may not be bound with wire to add stability to the structure. Check dams are often constructed throughout a drainage network such that they make up a system of erosion control structures that can affect large land areas.

Evaluations of check dams have generally focused on structural stability and/or functional response. Early assessment of range improvement practices implemented in the 1930s in southwestern United States (Peterson and Branson, 1962) indicated that, within a decade after construction, approximately two thirds of the structures built with rock rubble, including check dams, had failed. Although the failures were generally attributed to poor construction standards, the assessment raised serious doubts as to the advisability of using such treatments (Peterson and Branson, 1962). Many of the concerns related to construction have been addressed with information describing the importance of details such as keying into the channel bed and banks (NRCS Practice Standard; Heede, 1978). However, structural failure remains a concern because of the potential to exacerbate downcutting and erosion. Recent assessments point out that check dams may increase downstream erosion (Castillo et al., 2007; Porto and Gessler, 1999) associated with overfall and plunge pool erosion. In addition, structural failures can be associated with soil characteristics such as susceptibility to shrinking and swelling and dispersive soils (Nyssen et al., 2004).

Check dams have been used with varying degrees of success to control erosion and trap sediment. In Spain, watershed sediment yield was reduced 4.5-fold after the installation of 400 check dams on an 826-km^2 watershed (Romero-Diaz et al., 2007). In China, check dams have been constructed over large landscapes, with complimentary benefits of reducing sediment transfer and increasing the land area in the Yellow River Basin (Xu, 2005). In addition to affecting sediment transfers and yield, check dams alter runoff by reducing velocities and peak flows in response to deposition-induced channel slope reduction (Mishra et al., 2007). As runoff retention times are increased, soil moisture is increased (Nichols et al., 2012).

In 2008, a study was initiated on the Santa Rita Experimental Range (SRER) in southeastern Arizona to quantify the effect of check dams on runoff, sediment yield, and retention on small (4.0- and 3.1-ha) semiarid watersheds. Three years after construction, Polyakov et al. (2014) found that check dams did not significantly affect runoff from major rainstorms, as measured at the watershed outlet; however, during the course of the 3-year study, more than 50% of the measured sediment yield was retained by the structures. In addition, by the end of the 3 years, the check dams were filled to more than 80% of their capacity, suggesting limited potential for future sediment impact.

The objective of this article is to extend the analysis of Polyakov et al. (2014) to quantify the watershed and morphologic response 7 years after the construction of check dams, with emphasis on sediment retention and morphometric changes in the channel network through 2015. In addition, the physical condition of the check dams is documented.

MATERIALS AND METHODS

Study Site

The study site is located in the eastern Sonoran Desert 45 km south of Tucson in southeastern Arizona in the SRER (31°48′ 55.2″N; 110°51′4.4″W; 1,160 m above sea level) (Fig. 1). The SRER is located on an alluvial fan that extends from the base of the Santa Rita Mountains (McClaran et al., 2003). The climate is semiarid and is dominated by a summer monsoon season (July–September) (Sheppard et al., 2002) during which spatially variable high-intensity rainfall generates high-velocity flash flows. Winter rainfall is generally the result of frontal storms that generate lower-intensity rainfall and less rainfall. Mean annual precipitation from 1975 to 2015 was 385 mm (S.D., 111; watershed 5) and 391 mm (S.D., 121; watershed 6), with approximately 50% of total annual rainfall occurring from July through September (Polyakov et al., 2010). The annual mean maximum temperature was 29°C (S.D., 0.7).

In 1975, the USDA-ARS instrumented eight small subwatersheds within the SRER, and in 2008, two were selected for treatment with rock check dams. Watershed 5 (4.0 ha) and watershed 6 (3.1 ha) are instrumented with rain gauges and Santa Rita runoff-measuring flumes equipped with traversing slot sediment samplers (Smith et al., 1981). Watershed 5 is drained through a well-developed third-order channel network with 4% main channel slope gradient. In contrast, watershed 6, which is located 300 m from watershed 5, has a less developed second-order channel network and a steeper channel gradient (6%). The main channels on each watershed are up to 1.5 m deep. Channel alluvium was made up of coarse sands (1–3 mm). Soils on both watersheds are well-drained loamy sands and have low organic content, with a saturated hydraulic conductivity of between 50 and 150 mm h^{-1} (USDA, 2003). Reported sediment delivery rates, including estimation for missing data, for the period 1975 through 2008 were 3.16 t ha^{-1} $year^{-1}$ from watershed 5 and 0.22 t ha^{-1} $year^{-1}$ for the less-incised watershed 6 (Polyakov et al., 2010).

Vegetation on the watersheds is sparse, and much of the contributing area is bare ground. Vegetation on the SRER consists of shrubs (mesquite *Prosopis velutina* Woot., hackberry *Celtis pallida* Torr., catclaw acacia *Acacia greggii* Gray), cacti (cholla *Opuntia spinisor* Engelm, prickly pear *Opuntia engelmanni* Salm-Dyck, fishhook barrel *Ferocactus wisilizenii* Britt. and Rose), and grasses (black grama *Bouteloua eriopoda* Torr., Lehmann lovegrass *Eragrostis lehmanniana* Nees, Arizona cottontop *Digitaria californica* Benth., Santa Rita threeawn *Aristida glabrata* Vasey) (Martin and Morton, 1993). In 1974, before instrumentation and data collection, watershed 6 was treated to remove mesquite. When measured in 1986, the shrub cover on the untreated watershed was twice that of the treated watershed (Martin and Morton, 1993).

Check Dam Design and Construction

In November 2008, porous rock check dams were constructed in watersheds 5 and 6. A total of 27 check dams were constructed on watershed 5 and 10 on watershed 6. The dams were built using loose 10- to 30-cm (4- to 12-inch) rock that was placed by hand into wire mesh and thus were semipermeable. Check dam heights ranged from 0.15 to 0.6 m high and were up to 0.5 m thick. The check dams incorporated a low point near the center, and rocks were placed on the downstream side of each structure to prevent overfall scour. Each dam was keyed into the channel bed and banks.

The locations of the check dams were guided based on relationships developed by Heede (1978), taking into account channel slope and the stage of gully development. In general, each upstream dam was located at the upper extent of deposition induced by the closest lower dam. Deposition slope (Sd) was calculated using Heede's (1978) relationship:

$$\text{Sd} = 0.72 + 0.28 \times \text{So} \quad (1)$$

where S_0 is the average initial channel slope (in percentage). Tributaries were treated as continuation of the main channel, and the location of the first dam within each tributary was calculated based on the location of the nearest dam in the main channel. In practice, check dam locations were adjusted in response to local constraints such as the presence of large trees, tributary junctions, and channel bends.

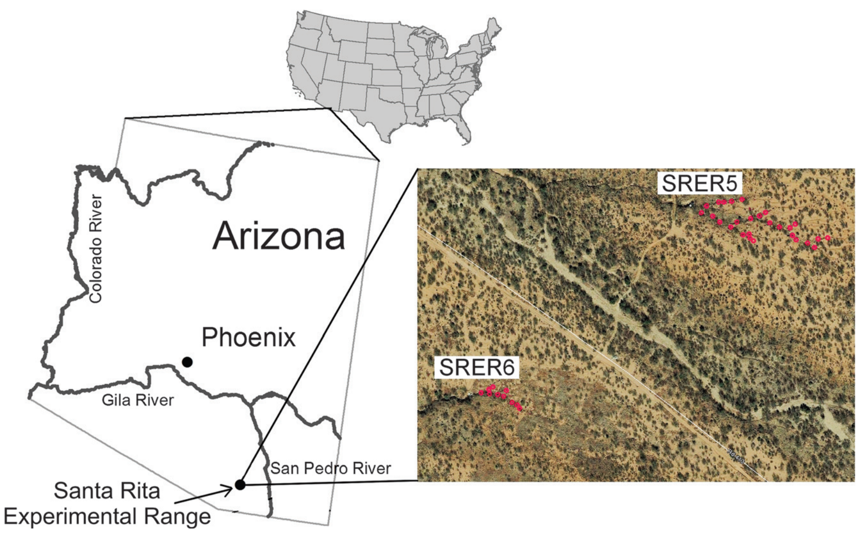

FIG. 1. Check dam study site location map showing watersheds 5 (SRER5) and 6 (SRER6) and check dam locations.

Instrumentation

Event precipitation, runoff, and sediment yield are measured at each watershed. Precipitation is measured with high temporal resolution weighing-type rain gauges. Runoff is measured with a Santa Rita supercritical depth runoff–measuring flume (Smith et al., 1981). Transported sediment is measured at the outlet of each watershed in conjunction with runoff using a traversing slot sediment sampler (Nichols et al., 2008) attached to each flume. Sediment sampling is initiated when flow depth through the flume reaches 6 cm. Sediment concentration is determined in the laboratory for each sample, and event sediment yields for each sampled event were computed by integrating the measured sediment concentrations multiplied by flow rates during the time of the runoff. In addition to runoff depth limitations to sampling, individual events may be inadequately sampled because of mechanical failures caused, for example, by a rock getting stuck in the intake slot or poor sample quality, for example, from overfilled bottles or debris. As a result, sediment yield is not measured for every runoff event. Polyakov et al. (2010) developed regression equations for missing data and estimated for the period of 1975 through 2008 that missing sediment data represented 46% and 33% of the sediment totals for watersheds 5 and 6, respectively.

Topographic and Sediment Measurement

Within each watershed, conventional topographic surveys were conducted in 2007 before check dam construction using a total station to measure longitudinal channel profiles and cross sections immediately up and down the channel from each dam. Subsequent surveys were conducted in each of the years from 2008 to 2012 and in 2015 using a Real Time Kinematic global positioning system. The volume (in cubic meters) of sediment stored behind the check dams was calculated as (Romero-Diaz et al., 2007):

$$V = 1/3 \times 1 \times A \qquad (2)$$

where l is the length (in meters), and A (in square meters) is the cross-sectional area of the sediment wedge at the dam.

Bulk samples of sediment deposited behind each check dam were collected and sieved to determine grain size distributions and texture. Samples were collected across the full width of the channel and included surface and subsurface sediment to a depth of approximately 10 cm.

Hydrologic Impact

The hydrologic impact of check dams was determined by evaluating the ratio of precipitation to runoff before and after construction. Double-mass curves of cumulative precipitation versus cumulative runoff were plotted and evaluated for breaks in the slope. As described by Searcy et al. (1960), a break in the slope of a double-mass curve indicates that a change in the constant of proportionality between precipitation and runoff has occurred. Linear regression was used to characterize relationships among precipitation, runoff, and sediment yield.

RESULTS AND DISCUSSION

Sediment Accumulation and Longitudinal Channel Profile Adjustment

By 2012, accumulated sediment had filled the check dams on watershed 5 to approximately 80% of their storage capacity defined by the height of the dams, and 62 m^3 had accumulated on watershed 5 (Polyakov et al., 2014). By 2015, an additional

TABLE 1. Reach Volume and Slope Change in Response to Check Dams on Watersheds 5 and 6 (M Refers to Main Channel and T Refers to Tributary)

	Volume Change, m^3		Reach Slope		
Check Dam	2008–2012	2012–2015	2008	2015	Change
5_M_1	1.30	0.55	0.055	0.032	0.023
5_M_2	7.82	1.48	0.024	0.021	0.002
5_M_3	4.85	2.61	Lateral scour		
5_M_4	3.80	3.05	0.039	0.028	0.011
5_M_5	2.79	2.24	0.044	0.026	0.018
5_M_6	5.15	4.30	0.053	0.020	0.033
5_M_7	2.26	1.18	0.043	0.034	0.009
5_M_8	0.75	0.36	0.056	0.026	0.030
5_M_9	9.70	6.75	Lateral scour		
5_M_10	4.97	4.20	0.050	0.032	0.019
5_M_11	1.78	1.91	0.066	0.035	0.030
5_M_12	1.30	0.26	Lateral scour		
Mean			0.048	0.028	
Mean reach slope change					0.020
5_T1.1	3.63	2.14	0.039	0.025	0.014
5_T1.2	0.49	0.64	0.080	0.046	0.034
5_T1.3	0.89	0.50	0.062	0.053	0.009
5_T1.4	3.46	2.79	0.051	0.038	0.013
5_T1.5	0.45	0.67	0.061	0.050	0.011
5_T2.1	2.33	1.91	0.070	0.066	0.004
5_T2.2	0.26	0.44	Lateral scour		
5_T2.3	0.15		Lateral scour		
5_T2.4	0.41	−0.09	0.058	0.040	0.018
5_T2A	0.16	0.22	0.103	0.027	0.076
5_T3.1*	0.29	0.97	0.095	0.070	0.025
5_T3.2*	0.11	0.12	0.121	0.088	0.033
5_T4.1	1.74	1.87	0.077	0.033	0.044
5_T4.2	0.49	1.09	0.047	0.044	0.003
5_T5.1	1.14	1.97	0.053	0.040	0.013
Sum	62.46	44.13			
Mean			0.061	0.039	
Mean reach slope change					0.021
6_M_1	0.13	1.13	0.022	0.019	0.004
6_M_2	0.15	0.44	0.082	0.060	0.021
6_M_3	0.04	0.48	0.037	0.031	0.006
6_M_4	0.09	0.77	0.055	0.041	0.014
6_M_5	0.03	0.65	0.108	0.043	0.065
6_M_6	0.09	0.32	0.089	0.040	0.049
6_M_7	0.21	0.33	0.066	0.050	0.015
Mean			0.066	0.041	
Mean reach slope change					0.025
6_T1.1	0.00	0.22	0.083	0.081	0.002
6_T1.2	0.00	0.25	0.088	0.058	0.030
6_T2.1	0.18	0.34	0.084	0.053	0.031
Sum	0.92	4.94			
Mean			0.071	0.047	
Mean reach slope change					0.024

Slopes were not computed for check dams that were subject to lateral scour.
*Structure buried and completely covered with sediment and vegetation.

44 m^3 accumulated, with individual dams retaining between 0.12 and 6.75 m^3 (Table 1). The highest accumulated volumes occurred on the main channel where the largest check dams were constructed. Although one tributary check dam experienced a net loss of 0.09 m^3 of sediment, by 2015, 80% of the check dams on watershed 5 were filled to capacity and, in several cases, sediment accumulated above the height of the down-channel dam (Fig. 2). In contrast, total sediment accumulation on watershed 6 was substantially less, which is expected based on the significantly lower erosion rates reported for that watershed (Polyakov et al., 2010). By 2012, less than 1 m^3 had accumulated, with an additional 5 m^3 accumulating by 2015.

Check dam construction was expected to reduce the slope profile along the reaches between the check dams in a step configuration with an abrupt elevation change at each check dam wall. The global slope remains obviously unchanged. Reach scale gradient adjustments were variable (Table 1), and local gradient adjustments between individual check dams were large. With the exception of cases where scour occurred, local gradient adjustment within the reach immediately up-channel of check dams on watershed 5 reduced the average reach slope by 35% (from 0.061 to 0.039) and 34% on watershed 6 (from 0.071 to 0.047). The minimum reduction in reach slope was 5.6% (from 0.070 to 0.066) on watershed 5 and 2.2% (from 0.083 to 0.081) on watershed 6. The maximum reduction in reach slope was 62.5% (from 0.053 to 0.020) on watershed 5 and 60.1% (from 0.108 to 0.043) on watershed 6. Within both watersheds, the reduction in mean reach gradient was greater in the main channel than in the tributaries.

Deposition slopes were expected to grade from the top of each check dam to the toe of the next upstream dam as described by Heede (1978). Although this pattern was seen in some reaches of watershed 5 (Fig. 2), there were several reaches where sediment accumulated above the anticipated grade and sediment was deposited above the height of the check dam. In two cases, this occurred where the check dam spacing was less than the computed, or design, spacing. An important point is that, in practice, check dam location is often determined by site-specific constraints, such as the presence of large trees. From repeat photography and field observation, generally, sediment accumulation above the height of a check dam occurred where vegetation has established (Fig. 3A and B, http://apps.tucson.ars.ag.gov/srcheckdams/). Vegetation acts to increase roughness and slow velocities, causing sediment to be deposited, thus developing a feedback mechanism whereby deposition can occur above the height of the dam. Textural analysis of deposited sediment indicated that the particle size distribution is dominated by sand with all of the measured samples containing greater than 90% sand size (1- to 2-mm) particles and between 1% and 5% gravel (>2 mm). Although not explicitly measured, the sand channel bed likely allows increased infiltration and soil moisture redistribution (Nichols et al., 2012) that enhance the capacity for further vegetation establishment and growth. Because dryland channels can store substantial amounts of sediment that is readily transportable (Lane et al., 1997), vegetation plays a critical role in stabilizing additional deposits induced by the check dams. Ultimately, vegetation will serve to control the evolution of the channel network.

Structure Condition

Although during the first 3 years after check dam construction, only one of the 37 check dams experienced structural degradation and had partially collapsed; during the next 4 years, five additional dams experienced lateral scour and channel bypass. In all cases, field observation of scour indicated that the structures needed to be keyed further into the channel banks. Two check dams experienced compensating plunge pool erosion and fill on the downstream side of the dams, displacing rocks placed to prevent downstream scour. In 2015, all impaired structures were rebuilt and rekeyed to channel banks to address lateral scour, undercutting, or downstream rock dispersal.

It is not uncommon for check dams to fail. In an assessment of loose rock check dams for gully control in Ethiopia, Nyssen et al. (2004) found that almost 40% of the check dams they surveyed failed during the 2 years after construction. Structural failures often result from the interacting factors of poor design and

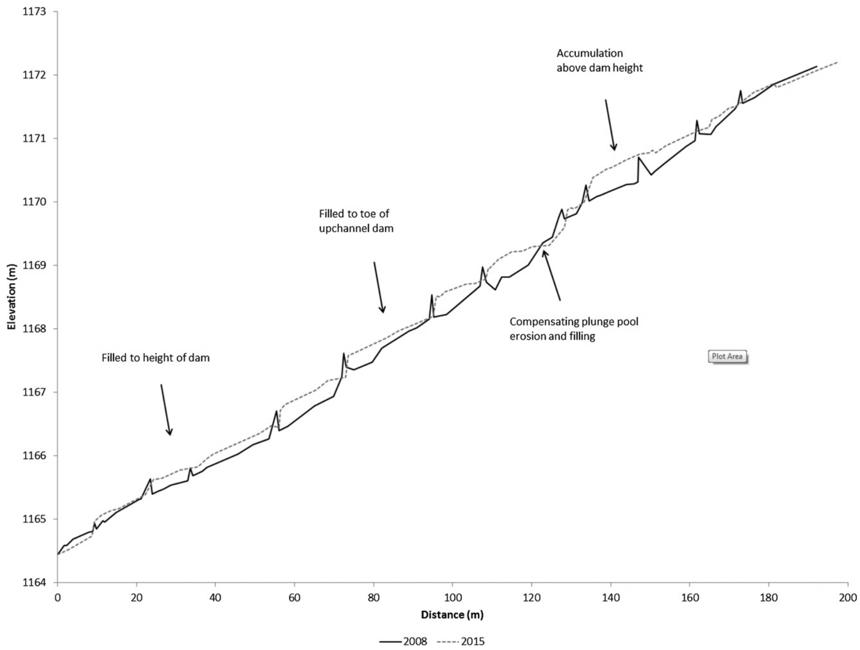

FIG. 2. Longitudinal channel profiles measured in 2008 and 2015 showing check dam–induced gradient changes on watershed 5.

FIG. 3. A, Repeat photographs showing vegetation and geomorphic impacts that occurred between November 2009 and January 2016 on a tributary channel in watershed 5. B, Repeat photographs showing vegetation and geomorphic impacts that occurred between November 2009 and January 2016 on the main channel in watershed 5.

construction technique with infrequent high-magnitude runoff events. In 2013, watershed 5 experienced the second largest peak runoff rate on record (details below), which likely contributed to lateral scour and dispersal of rocks that made up the five structures that failed. The effectiveness of check dams for grade stabilization and erosion control depends on maintenance to ensure structural integrity and minimize exacerbating erosion problems.

Hydrologic Impact

Watersheds 5 and 6 are located approximately 300 m apart, and thus long-term average annual precipitations of 385 and 391 mm, respectively, are similar. With the exception of well below average precipitation in 2009, annual precipitation (*P*) in each of the years after check dam construction were close to measured long-term average annual precipitation, ranging from 336 to 357 mm and from 329 to 412 mm on watersheds 5 and 6, respectively (Table 2). From 2009 through 2015, 91% and 95% of runoff (*Q*) occurred during monsoon season months from July through September on watersheds 5 and 6, respectively. However, runoff response varied between the watersheds, with a higher proportion of precipitation yielding runoff on watershed 5 than on watershed 6. A plot of precipitation and runoff during monsoon season months during postconstruction years (Fig. 4) and runoff generated on July 5, 2013, highlight the contrast in watershed runoff response. On July 5, 2013, 68 mm of precipitation were delivered in 81 min on watershed 5 and 67 mm on watershed 6. This storm generated 35 mm of runoff on watershed 5, with a peak runoff rate of 105 mm h^{-1}, which is the second largest peak runoff rate recorded on this watershed since 1975 and corresponds to slightly less than a 100-year recurrence interval runoff event. In contrast, runoff on watershed 6 was 66% less (12 mm; peak runoff rate, 39.5 mm h^{-1}). The spatial heterogeneity of runoff response to similar precipitation input is likely attributable to the difference in vegetation and physical watershed characteristics such as the extent of channel development.

The relation between cumulative precipitation and cumulative runoff from 2005 to 2015 is shown for watersheds 5 and 6 in Fig. 5. The double-mass plots show clear evidence of a change in the *P*/*Q* ratio on both watersheds after check dam construction in 2008. By 2010, the slope of the *P*/*Q* relationship on watershed 5 had returned to the pre–check dam rate, indicating that the overall influence of check dams on event runoff was limited to the first years after construction. This is attributable to accumulated sediment, which has reduced the storage capacity of the check dams, thus limiting their impact on runoff. By 2013,

TABLE 2. Long-term and Study Period Annual Precipitation and Runoff Characteristics for Watersheds 5 and 6

	Watershed 5		Watershed 6	
Year	Precipitation, mm	Runoff, mm	Precipitation, mm	Runoff, mm
Average 1975–2015	385	25	391	7
S.D. 1975–2015	111	23	121	11
2009	175	3	182	0
2010	399	26	412	1
2011	383	56	385	5
2012	336	79	329	16
2013	345	62	342	15
2014	352	43	378	2
2015	357	22	368	0
Average 2009–2015	335	42	342	6
S.D. 2009–2015	74	26	76	7

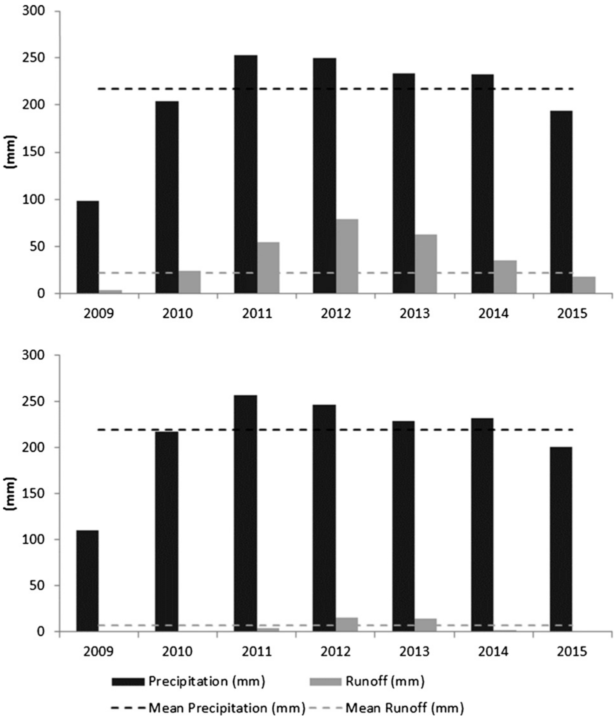

FIG. 4. Post–check dam construction cumulative July, August, and September precipitation and runoff measured at watersheds 5 (top) and 6 (bottom).

when the 100-year flood event occurred, the check dams no longer influenced the relationship between precipitation and runoff. In contrast, the influence of check dams on the P/Q relationship for small flows at watershed 6 persists. The P/Q ratio returned to the predam pattern in response to two large runoff events at watershed 6 (September 10, 2012: P = 63 mm, Q = 12.5 mm; and July 5, 2013: P = 67 mm, Q = 12.3 mm) but remains at the new P/Q ratio. This indicates that the check dams on watershed 6 influence watershed outlet runoff during small events but not during large events. Because the check dams on watershed 6 are not yet filled to capacity with sediment, the available storage volume can accommodate runoff. If the storage volume is large in comparison with runoff volume, as is the case during small flows, then the relative impact of the check dams on outlet runoff volume can be significant in reducing through flow.

Outlet Sediment Yield

Prior analysis of the impact of check dams in watershed 5 on annual sediment yield during the 4 years after construction determined a twofold decline in sediment yield at the watershed outlet (Polyakov et al., 2014). That analysis was based on evaluation of the regression relation between peak runoff rate, which has been shown to be the best predictor variable for sediment yield on watershed 5 (Polyakov et al., 2010) and sediment yield. By 2015, no difference was seen in the relation between peak runoff rate and sediment yield when comparing events sampled from 1976 to 2008 with those sampled from 2009 to 2015 (Fig. 6), indicating that the impact of check dams on outlet sediment yield is relatively short lived. In addition, high-magnitude runoff events account for a disproportionate amount of overall sediment yield, and these events are not influenced by the presence of check dams. For example, as reported by (Polyakov et al., 2014), the largest 10% of storms accounted for 66% of total measured sediment yield on watersheds 5 and 6. Check dams have a limited capacity to retain runoff, and thus high-magnitude events are less influenced by their presence, especially once the available retention capacity is reduced through deposition, as was seen in watershed 5. In addition, because sediment delivery to the outlet of both watersheds is transport limited and sediment supply is abundant, the check dams have little influence on the amount of sediment transported. Before check dam construction, the average sampled sediment concentration on watershed 5 was 0.026 (S.D., 0.027) and, after construction, the average sampled concentration was 0.034 (S.D., 0.025) but not significantly different.

CONCLUSIONS

Understanding how check dams impact watershed hydrology and geomorphic response is important for informing restoration potential and expectations. From this ongoing research, the following conclusions can be drawn after 7 years of post–check dam observation and measurement:

Low-tech porous rock check dams can be used to reduce local channel gradient, induce deposition, and mitigate channel downcutting on degraded semiarid headwaters where their small size limits the potential for catastrophic failure. Backfilling can be rapid in semiarid watersheds characterized by high sediment loads, filling to capacity in three to seven seasons of runoff. High sediment loads also contributed to deposition slopes that were steeper than design computations, and as a result, several dams were buried and grassed over with sufficient density that the dams had to be searched for to complete topographic surveys.

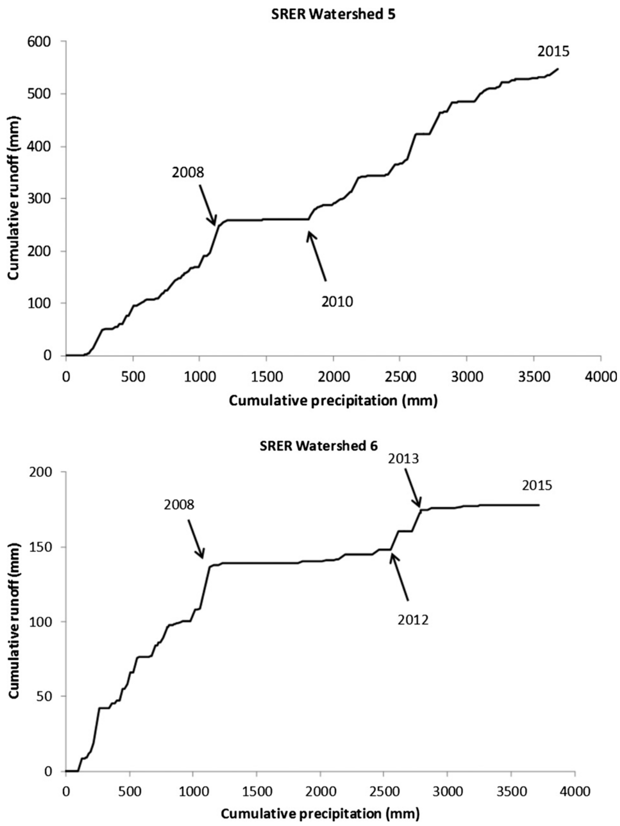

FIG. 5. Accumulated precipitation versus accumulated runoff measured on watersheds 5 and 6.

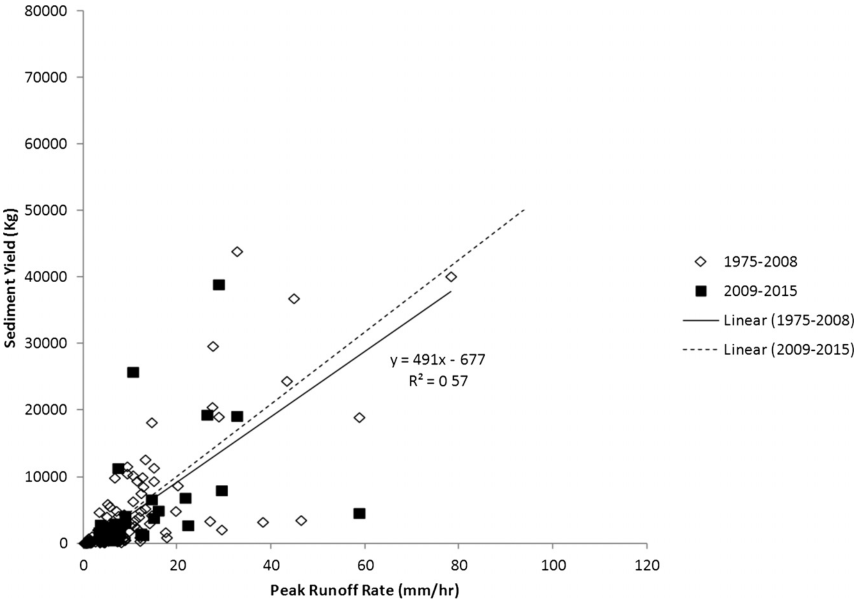

FIG. 6. Event sediment yield versus event peak runoff rate before and after check dam construction.

Check dams have lesser influence on watershed outlet peak runoff rates and sediment yield, suggesting that watershed outlet measurements do not sufficiently characterize the influences of structural practices on watershed response. The initial impacts of reducing the number of small runoff events that reach the watershed outlet and alteration to rainfall runoff ratios are lessened as the check dams backfill with sediment.

A critical aspect of constructing check dams as part of an overall restoration strategy is maintenance. Although only one check dam failed in the first 3 years after construction in this study, five dams experienced lateral scour during the subsequent 4 years. These structural problems are attributable to the occurrence of the largest-magnitude runoff on record. However, although not predictable, precipitation and runoff are highly variable in semiarid regions and large-magnitude, damaging, runoff events should be expected. The ability to withstand the impact of high-magnitude floods is attributable to proper keying into channel bed and banks.

Vegetation plays a critical role in site stabilization and overall ecosystem restoration. Although not measured as part of this study, repeat photography and field observations show distinct increases in vegetation in response to the check dams. Because the expectation of long-term site stability hinges on establishment of vegetation on the channel bed and along the channel margins, specific research to quantify vegetative response is needed.

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