Hydrologic Response of Streams Restored with Check Dams in the Chiricahua Mountains, Arizona

Article *in* River Research and Applications · March 2015

DOI: 10.1002/rra.2895

Laura M. Norman
United States Geological Survey

Evan Gwilliam
National Park Service

David Guertin
The University of Arizona

James B. Callegary
United States Geological Survey

RIVER RESEARCH AND APPLICATIONS

River Res. Applic. (2015)

HYDROLOGIC RESPONSE OF STREAMS RESTORED WITH CHECK DAMS IN THE CHIRICAHUA MOUNTAINS, ARIZONA

L. M. NORMAN[a]*, F. BRINKERHOFF[b], E. GWILLIAM[c], D. P. GUERTIN[d], J. CALLEGARY[b], D. C. GOODRICH[e], P. L. NAGLER[f] AND F. GRAY[g]

[a] *Western Geographic Science Center, U.S. Geological Survey, Tucson, Arizona, USA*
[b] *Arizona Water Science Center, U.S. Geological Survey, Tucson, Arizona, USA*
[c] *Sonoran Desert Network, National Park Service, Tucson, Arizona, USA*
[d] *School of Natural Resources and the Environment, University of Arizona, Tucson, Arizona, USA*
[e] *Southwest Watershed Research Center, USDA Agricultural Research Service, Tucson, Arizona, USA*
[f] *Southwest Biological Science Center, Sonoran Desert Research Station, U.S. Geological Survey, Tucson, Arizona, USA*
[g] *Geology, Minerals, Energy, and Geophysics Science Center, U.S. Geological Survey, Tucson, Arizona, USA*

ABSTRACT

In this study, hydrological processes are evaluated to determine impacts of stream restoration in the West Turkey Creek, Chiricahua Mountains, southeast Arizona, during a summer-monsoon season (June–October of 2013). A paired-watershed approach was used to analyze the effectiveness of check dams to mitigate high flows and impact long-term maintenance of hydrologic function. One watershed had been extensively altered by the installation of numerous small check dams over the past 30 years, and the other was untreated (control). We modified and installed a new stream-gauging mechanism developed for remote areas, to compare the water balance and calculate rainfall–runoff ratios. Results show that even 30 years after installation, most of the check dams were still functional. The watershed treated with check dams has a lower runoff response to precipitation compared with the untreated, most notably in measurements of peak flow. Concerns that downstream flows would be reduced in the treated watershed, due to storage of water behind upstream check dams, were not realized; instead, flow volumes were actually higher overall in the treated stream, even though peak flows were dampened. We surmise that check dams are a useful management tool for reducing flow velocities associated with erosion and degradation and posit they can increase baseflow in aridlands.

KEY WORDS: check dams; restoration; semi-arid watersheds; water budget; runoff ratio

Received 16 November 2014; Revised 30 January 2015; Accepted 10 February 2015

INTRODUCTION

Arid and semi-arid regions often experience flooding in monsoonal summer months, when precipitation is delivered via short, intense rain events, causing erosion in channels and degradation of stream habitat. Aridland-based cultures have adapted ways to slow and retain runoff using various rock detention structures (Herold, 1965; Doolittle, 1985; Fish *et al*., 2003; Pandey *et al*., 2013; Waterfall, 2004). Studies have shown that such detention structures can reduce peak flows and floods (Stabler, 1985; Lenzi, 2002; Norman *et al*., 2010, 2014) and also reduce erosion (Castillo *et al.* 2007; Polyakov *et al*., 2014). In a desert wetland, detention structures demonstrate increases in surface water and increased vegetation despite drought (Malcom and Radke, 2008; Radke, 2013; Norman *et al*., 2014). Nichols *et al*. (2012) found increased soil moisture at channels treated with check dams versus those without. Dams constructed by the North American beaver (*Castor canadensis*) improve watershed conditions by stabilizing and extending streamflow (Stabler, 1985; DeBano and Heede, 1987), yet little research documents the extent to which man-made detention structures might impact long-term aridland water supplies.

Restoration has been a major goal at the El Coronado Ranch (EC), in the West Turkey Creek watershed, Chiricahua Mountains of Southeast, Arizona, USA (Voeltz, 2010; Dobie, 2012). Thousands of check dams were constructed by hand in small channels, usually less than 60 cm in height, and spaced at intervals of 6–20 m (Minckley, 1998; Figure 1). A few dams have failed, redistributing their rocks, and others maintained and reconstructed. According to Minckley (1998), check dams at EC maintain a failure rate of less than 1.0% over a 10-year period.

---

*Correspondence to: L. M. Norman, U.S. Geological Survey, Western Geographic Science Center, 520N. Park Ave, Ste. #102K, Tucson AZ 85719, USA.
E-mail: lnorman@usgs.gov

Figure 1. Photograph of check dams in the Turkey Pen sub-watershed of West Turkey Creek, southeast Arizona. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

Anecdotally, we see that these check dams are not just reducing peak flows but also impacting surface-water availability in the treated watershed. To quantitatively document these hypotheses, we established an experiment to compare the treated sub-watershed with an adjacent sub-watershed (control) that has not been treated with check dams, based on the assumption that the two respond in a predictable manner together. We present an innovative modification of a new stream-gauging methodology and compare the hydrological response to document the influence of check dam restoration.

MATERIALS AND METHODS

Study area

West Turkey Creek (WTC) originates in the higher elevations of the Chiricahua Mountains, of the Madrean Archipelago (a.k.a. Sky Island) region of southwestern North America (Omernik, 1987; Warshall, 1995; Skroch, 2008; Figure 2). The intermittent-wet WTC contributes to groundwater replenishment for domestic and agricultural water in the Willcox Basin (Arizona Department of Water Resources, 2009). WTC was formed by the Turkey Creek Caldera, an Oligiocene center that is deeply eroded, exposing hypabyssal volcanic and shallow plutonic rocks (Marjaniemi, 1969; Du Bray and Pallister, 1991, 1995, 1999; Graham, 2009). An erosion-resistant dacite porphyry complex forms much of the highlands, and erosion of the soft, ash-rich white layer at the base of a thick rhyolite tuff is obvious. Mixed deciduous and evergreen woodlands mapped by Halvorson *et al.* (2002) are stratified by elevation.

Turkey Pen (TP) is the tributary where restoration began around 1983, with continued grazing (Figure 2). The sub-watershed is 769 ha and approximately 5 km long, with a 554-metre change in elevation, with no exposed bedrock and very little incision (Figure 1). Over 2000 check dams

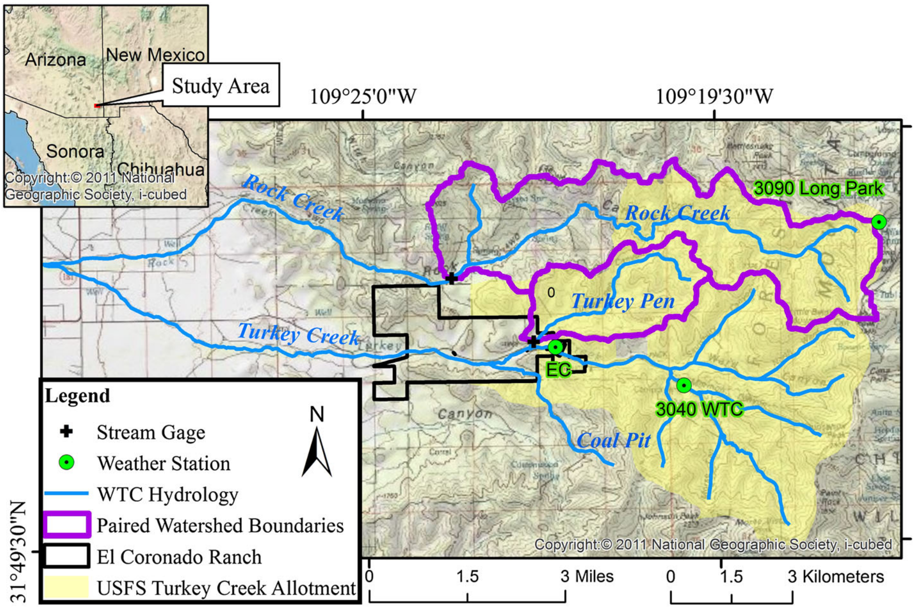

Figure 2. Location map depicting gauges, weather stations, streams, topography, watershed boundaries and land ownership. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

DOI: 10.1002/rra

are installed uniformly, creating low gradient slopes with low banks, which cause flow to spread across the terrace and through vegetation. Soils are mainly fine sands with much organic material deposited above the dams, creating wide alluvial deposits, ranging in widths over 3–6 m. The check dams create a small scour pool at the downstream base, and flow is confined by mild, sloping banks strewn with trees and boulders. TP has vegetation in the channel, composed mainly of single-stem and clump grasses along with other annuals and algae in longer-lived pools. A few trees are dispersed in the main channel with root masses and trunks that create some obstructions.

Rock Creek (RC) was selected as our control site, located just north of the ranch on U.S. Forest Service land, also grazed by cattle, but with no check dams (Figure 2). The majority of flow occurs through deep channels with large boulders and overexposed bedrock. The watershed is three times as large as TP, approximately 2405 ha, with approximately 10 km from outlet to peak and topographic relief variance approximately 1238 m. Despite the differences in size, similarities between the control and treated sub-watersheds include slopes, location and proximity, soils, land cover, geology and also in biology, documented by scientists tracking the Sonoran mud turtle (*Kinosternon sonoriense*; Van Loben Sels *et al*., 1997). Minckley (1998) monitored these two sub-watersheds to document impacts of check dams but found the need to install continuous-recording devices, which is what we did.

Hydrology

The water budget describes flows into and out of the system as:

$$\mathrm{P = Q + ET + \Delta S + I\text{-}O} \tag{1}$$

where *P* is precipitation, *Q* is runoff, *ET* is evapotranspiration, ΔS is the change in water storage (in soil or the bedrock), *I* is groundwater inflow to the watershed aquifer and *O* is groundwater outflow. Groundwater inflow (*I*) is often small, relative to precipitation, and little water is lost to groundwater outflow (*O*) from the system due to the thickness and low hydraulic conductivity of bed sediments and minimal fractures. We roughly estimate *ET* as 67% (U.S. Geological Survey, 1990), although it is likely that the enhanced vegetation identified in the treated watershed would use more water than the sparser riparian zone found in our control. Using these assumptions, we rearrange the water budget to solve for the change in storage:

$$\mathrm{\Delta S = (P\text{-}67\%)\text{-}Q} \tag{2}$$

During rainfall, precipitation soaks into the soil before exceeding infiltration capacity and running off. The initial capacity of a dry soil is high but decreases over time depending on rainfall (intensity and duration), vegetation (interception and transpiration) and soil characteristics (texture and structure), as well as on the antecedent soil moisture content (previous rainfall or lack of). Rainfall–runoff ratios are calculated by dividing runoff depth by rainfall depth over a catchment area (*Q*/*P*). If the soil moisture content is assumed to temporarily increase by the difference between *P* and *Q*, then the magnitude of short-term ΔS can be examined (Osborn and Lane, 1969; Canfield and Goodrich, 2003).

Precipitation (P). Precipitation within the WTC ranges between 38 and 66 cm of rain per year, most of which is received from July through mid-September (Fuller, 2014) and occurring as isolated, cellular, high-intensity thunderstorms (Goodrich *et al*., 1997). Rain gauges separated by more than 5 km in this region are not adequate to represent rainfall/runoff modelling due to spatial rainfall variability (Goodrich *et al*., 1995). Three gauges exist at the perimeters of the combined approximately 32 km^2 study area (Figure 2). The WTC ALERT gauge 3040 (31°51′36.00″N, 109°20′9.00″W) is approximately 0.6 km south of the edge of the TP watershed at 1907 m elevation, and the Long Park ALERT gauge 3090 (31°53′46.30″N, 109°17′0.30″W) is at the peak of the RC watershed, elevation 2768 m (Fuller, 2014). These event-based tipping buckets report in real-time whenever there is 1 mm of precipitation. A Davis Instruments Weatherlink data-logger station is located at the EC (31° 52′ 7.8564″, 109° 22′ 2.3478″), elevation 1779 m, approximately 0.25 km from the perimeter of TP and 0.5 km from its outlet.

Runoff (Q). We modified the Continuous Slope Area (CSA) method (Smith *et al*., 2010) to document runoff at both the treated and control sites. This entailed creating a continuous record of stream stage, measuring channel characteristics and capturing periodic measurements of discharge at gauge locations as described in the subsequent discussions. This information was compiled to develop the stage–discharge relationship (rating curve) and then a hydrograph (Stewart *et al*., 2012; Perlman, 2014).

The CSA method was developed by the U. S. Geological Survey's Arizona Water Science Center (Smith *et al*., 2010) to estimate discharge at medium and high flows over a hydrograph without the need for direct measurements. Stewart *et al*. (2012) outline the assumptions, limitations, potential errors and uncertainties associated with the CSA method. Smith *et al*. (2010) recommend that at least four stations be used to estimate discharge per CSA gauge, where each station consists of a pressure transducer at a surveyed cross-section within the slope-area reach. Slope-area reaches are long, straight and somewhat trapezoidal shape and have a gentle slope (Dalrymple and Benson, 1967). Due to

DOI: 10.1002/rra

limited project resources, each modified CSA gauge in this study consisted of only two stations, upstream and downstream. The pressure transducers, Solinst® Model 3001 Levelogger Junior Edge dataloggers (Georgetown, Ontario, Canada), were set to measure water level and temperature every 15 min. These were inserted into steel holsters and bolted instream at an angle of between 45° and 60° facing downstream on 21 June 2013 at RC (Figure 3a) and 24 May 2013 at TP (Figure 3b). A barometric pressure transducer was installed at the EC lodge (elevation 1781 m) to correct for local air pressure.

It is not required to have direct measurements of stage and discharge for the CSA gauge method for medium–high flows, but it is necessary for low flow. Calculating discharge requires surveys of channel dimensions (Turnipseed and Sauer, 2010). Surveys are required for estimating cross-sectional areas that must be updated regularly. A real-time kinematic global positioning system base station with differential corrections and Total Station Survey were used to acquire precise bearings and cross-section surveys. A flow meter was used to capture in-stream wading measurements of stage and discharge at varying levels and volumes of flow to help develop stage–discharge relationships.

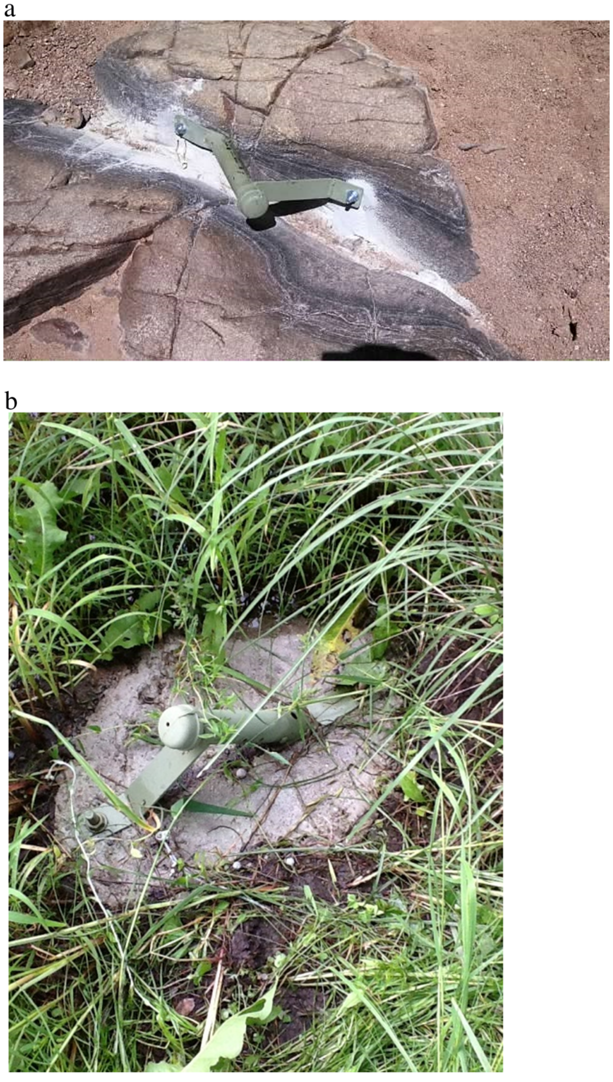

Figure 3. Photographs of steel holster constructed to house the leveloggers at (a) untreated watershed and (b) treated watershed. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

Cross-section geometries were input to the Hydrologic Engineering Center's River Analysis System (HEC-RAS; Brunner, 2002) model with the discharge measurements to develop an expanded rating table for each site. Manning's Roughness Coefficients (*n*-values) were applied to indirect measurement computations (Aldridge and Garrett, 1973), and HEC-RAS was used define the upper end of the rating. Slope-Area Computation measurements, one in-stream wading measurement and gauge height of zero flow (GZF) observations were used to define the low end.

Over 12 000 stage measurements were recorded at each of the pressure transducers. Data from the upstream (primary) stations were used for gauge height, and data from downstream were used to acquire water-surface slope between them. Our modified-CSA gauges were effective if flow over them was deep enough to have a continuity of water-surface slope, which occurred only during high-flow events. During low flows, discharge was computed by applying gauge-height data from the primary station to the stage-discharge rating. To estimate the total volume of runoff per watershed, the area under the curve of each hydrograph was calculated using the Trapezoid or Quadrature Rule for approximating definite integrals (Kreyszig, 1993).

RESULTS

Precipitation

A variety of methods was considered to interpolate *P* for each watershed using different combinations of the gauge data, including daily means from each station. The two-tail *p* and the *t*-stat demonstrate no significant difference between the three gauges ($p = 0.53$, 0.73, 0.83), and the Pearson's test values show medium–high correlation. The three gauges report rainfall with the same daily mean at a 95% confidence level. Therefore, we used the arithmetic-mean technique to calculate areal precipitation using the daily averages of all three rain-gauges (Brooks *et al.*, 1997). The first precipitation recorded during the study was 1 July 2013 and the last was 20 September 2013 (Table I; Figure 4). The gauge located at the EC suffered an outage between 7 September 2013 and 20 October 2013. Average precipitation for the entire study period (1 July–25 October) is 2.99 mm/day.

DOI: 10.1002/rra

Table I. Total precipitation recorded per month and study timeframe (cm).

July	August	September	October	Total
16.1	14.4	4.2	0	**34.8**

Runoff

Seasonal hydrographs were developed using the stage data and the rating curves to quantify discharge. Figure 4 portrays the hyeto-hydrographs for 116 days, beginning 1 July (first rain)–October, where maximum volumetric flow rate per day is compared with precipitation. It is noted that neither CSA gauge indicated runoff response to precipitation falling at the beginning of July; we assume this is due to moisture content prevailing in the soils and transmission losses.

The runoff values for TP ($M = 0.0047$, $SD = 0.0002$, $N = 11190$) were significantly different from RC ($M = 0.0106$, $SD = 0.0003$, $N = 11190$) using the two-sample *t*-test for unequal variances, $p < 0.001$. Total runoff volumes are 107 082 cubic metres in RC and 46 976 cubic metres from TP. This was normalized by dividing runoff volumes by the drainage areas; the area depth in RC (24.05 km^2) is 0.44 cm, and in TP (7.69 km^2) is 0.61 cm for the entire study.

Table II shows the ratio (percent of rainfall accounted for by runoff) from month to month, normalized for differences in area between the watersheds. The ratio in both watersheds are low in July, due to low antecedent soil moisture content, yet as the soil profile becomes saturated in August, runoff is generated equally in both watersheds. In September, rainfall begins to exceed infiltration capacity regularly in the treated watershed (TP) creating a ratio that is more than double that in the untreated watershed (RC). Because there was no rain

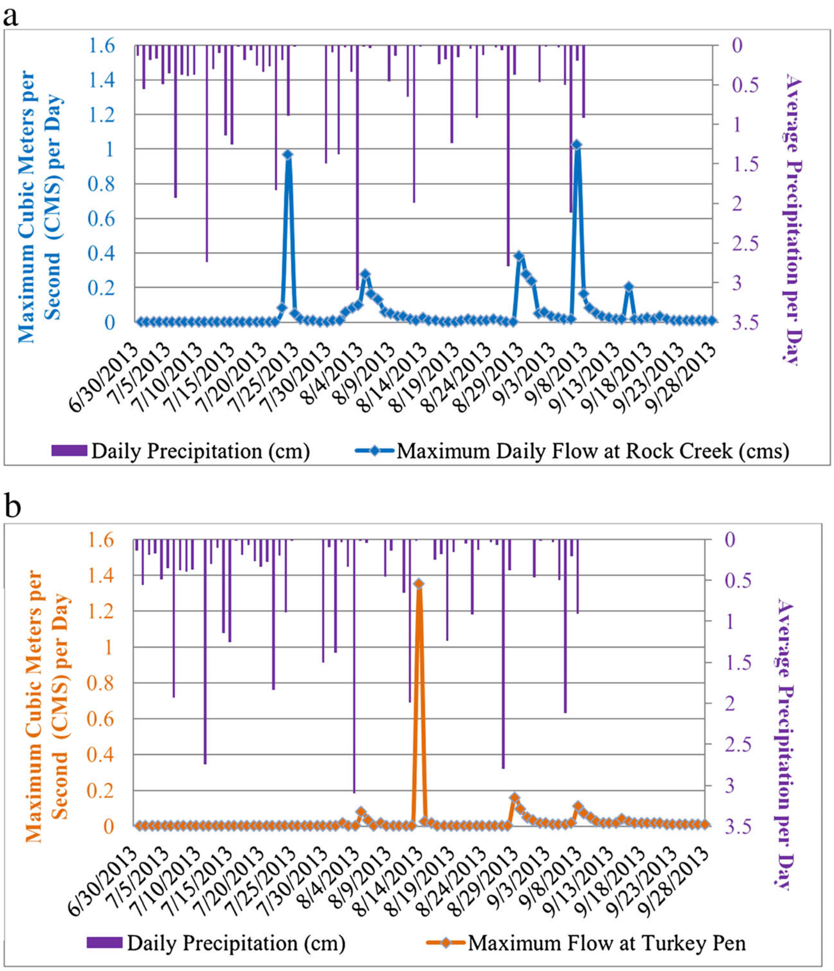

Figure 4. Hyeto-hydrographs portray the maximum rate of flow (discharge) per day versus time past each continuous slope area gauge, plotted against daily total precipitation (averaged from available rain gauges) at (a) untreated watershed and (b) treated watershed. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

DOI: 10.1002/rra

Table II. Total volumes of runoff and precipitation in paired watersheds with runoff ratios (from July–September).

	Untreated/control (RC)			**Treated (TP)**		
	***Q* volume (total cubic metres)**	**Precipitation (monthly total * watershed size, in cubic metres)**	**Runoff (%)**	***Q* volume (total cubic metres)**	**Precipitation (monthly total * watershed size, in cubic metres)**	**Runoff (%)**
July	12 959	3 878 490	0.33	0	1 238 090	0
August	58 139	3 468 960	1.68	18 561	1 107 360	1.68
September	34 264	1 011 780	3.39	27 560	322 980	8.53
October	1720	0	0	855	0	0

in October, we could not create a ratio but the volumes of water per watershed size were greater in TP.

DISCUSSION

Arid and semi-arid lands in the southwestern United States and northwest Mexico are characterized by relative extremes in the hydrologic cycle, including high ET, low precipitation with high-intensity storms, low annual runoff with high volume, short duration, storm flow runoff as well as channel-transmission losses (Branson *et al.*, 1981; Hernandez *et al.*, 2000; Martín-Rosales *et al.*, 2007). A cycle can be recognized within the treated watershed, for which check dams fill in with sediment, water is detained and water availability increases. Regularly spaced check dams transform gullies by decreasing gradients, increasing roughness and spreading flow.

Data in this study show that RC is a more flashy system than TP, with higher transmission losses and water moving out of the watershed immediately following the onset of precipitation. The majority of data showed that rain events in RC were followed by high runoff response, where flows reach 0.2 cm in 7 days during with minimal response at TP. One exception to this occurred on 14 August, with an increase in rainfall at TP, not reflected in either of the ALERT gauges or at RC. The rain gauge at the EC reported 5.2 cm, the greatest rainfall recorded during the study, with an average rate of 20.8 mm/h, over 150 times the average (0.12 mm/h) this summer. The modified-CSA at TP reported 1.346 cm (Figure 4b) and then maintained the flow for 24 h at an average of 0.081 cm. After the peak on 14 August, there were no significant silt or sand deposits in TP, flow was relatively clear. The only evidence of this extreme event was that the grass in the floodplain had lain down.

Check dams create more storage space for groundwater, resulting in higher water tables over time and increasing runoff rates (called rejected recharge). Energy is reduced by the intersection with both check dams and the detention step-pool morphology —allowing for a very slow, controlled but steady, release of water (Lee and Ferguson, 2002; Milzow *et al.*, 2004; Castillo *et al.*, 2013). In TP, the shallow soil is underlain by rock or finer soils, allowing the soil pores to be saturated by rainfall and subsequently generate runoff (Juracek, 1999). In RC, runoff is generated when rainfall exceeds infiltration, typical for deep soils in arid and semiarid regions, (Beven, 2004).

A common concern is that check dams harvesting water in the upper reaches of the watershed will decrease surface flows to lower regions, but this study documents the opposite. The runoff ratio in the treated watershed (TP) increased over time to more than double the control (RC) during the study. The total volume of runoff per watershed, normalized by dividing by the drainage area (area depth) is 0.44 cm in RC and 0.61 cm in TP. Heede (1977) and DeBano (1984) noted similar results of creating a saturated zone within the sediment trapped behind check dams in gullies of the Alkali Creek drainage and posit that small dams may be effective in increasing summer flows because of this.

Limitations to our study

In semiarid environments, runoff response decreases with increasing watershed size due to potential increase in channel-transmission losses and because runoff-producing storms are limited in spatial extent (Osborn and Lane, 1969; Goodrich *et al.*, 1994, 1995; Canfield and Goodrich, 2003). Without having an exact replica from one paired sub-watershed to the next, the direct comparison from one to another is full of potential error due to even the slightest differences in size, elevation, soil type, geology, vegetation, rainfall, topography, geomorphology and so on. However, the influence of land management on water supplies has been successfully documented using the paired-watershed approach and, hence, contributes to our understanding of the hydrologic cycle and the effects of management on it (Kincaid *et al.*, 1966; Hornbeck, 1973; Bosch and Hewlett, 1982; Beschta *et al.*, 2000; Ziemer and Ryan, 2000; Huang *et al.*, 2003; Veum *et al.*, 2009). Another limitation of the study is the lack of long-term monitoring (Wilm, 1949), especially in the case of wintertime rainfall, which is typically lower intensity, produces less runoff, and, due to its less erratic patterns, is presumably less sensitive to changes in infiltration (Kennedy *et al.*, 2013).

We cannot present these results without acknowledging the potential for error in our assumptions and the limited monitoring both in time and space. It is recognized that more rain gauges would better capture spatial distribution of rainfall, and field validation data would improve ET estimates. We also note that CSA gauges are not intended for measuring low-flow data-collecting, that processing labour can introduce error, and that ideally, at least four pressure transducers should be used at each CSA gauge (Smith *et al.*, 2010). Other errors can be introduced based on instrumentation, data processing and analysis variance. While a complex field investigation and hydrological modelling beyond the scope of this study would be required to further investigate, and scale and spatial variability are recognized as problems that need to be addressed, there are limited data sets for studying these problems, and ours is a first attempt.

CONCLUSIONS

The restoration of riparian corridors using rock check dams, when streams have been altered by cattle grazing and other disturbances, is found to promote a cascade of beneficial processes to the larger watershed and ecosystem. The treated watershed demonstrates a reduction in the average rate of flow compared with the control, by more than one-half, most notably in size and duration of peak flow. Check dams enable deposition and storage of loose, sandy soils with high infiltration capacities to dominate the treated channel and create more capacity to detain water upstream. Sediment detention provides additional substrate for riparian plants, further increasing the potential for infiltration and groundwater storage capacity. The treated channel maintains moisture over time that ultimately increases and extends baseflow via slow-release through check dams. The treated watershed is able to sustain approximately 28% more flow volume in our study than the untreated watershed (per unit area). This is groundwater-supported flow, most notable after rainfall-induced runoff has finished in channels treated with check dams.

In the realm of ecosystem services, it is warranted to consider the cost of installing and maintaining check dams versus the cost of water, habitat and carbon provisioning, flood control and erosion prevention. The potential for natural erosion processes, like gullying, to increase losses of water storage, supports more forward-thinking solutions for prevention and sustainability. We anticipate that historical adaptations to aridity and drought, like the installation of rock detention features, may pave the way for modern societies to adapt to future climate change. In semi-arid watersheds, precipitation is sufficiently rare that maintaining groundwater levels, and consequently baseflow, is critical for creating functioning watersheds and to the survival and/or expansion of aquatic and riparian ecosystems.

ACKNOWLEDGEMENTS

This research was conducted with support from the Land Change Science (LCS) Program, under the Climate and Land Use Change (CLU) Mission Area of the U.S. Geological Survey (USGS). The National Park Service's Sonoran Desert Network (NPS SODN) supplied equipment for the study in relationship to nearby Chiricahua National Monument. We appreciate the peer reviews done by Stephen Wiele and Ann Youberg. Many thanks to Valer and Josiah Austin (EC; Cuenca Los Ojos Foundation); Joel Sankey, Miguel Villarreal, Leila Gass, Jeff Cordova and Hanna Coy (USGS); Jon Pelletier and Edward Glenn (University of Arizona); Kara Raymond (NPS); Erin Boyle (National Weather Service); Michele Girard and Duane Bennett (USFS, Coronado National Forest); Ryan Faught and Chelsea Smith (University of Oklahoma); Ron Pulliam and David Seibert (Borderlands Restoration); and Gerry Norman for all their help making our research a success. References to commercial vendors of software products or services are provided solely for the convenience of users when obtaining or using USGS software. Such references do not imply any endorsement by the U.S. Government.

REFERENCES

Aldridge BN, Garrett JM. 1973. Roughness coefficients for stream channels in Arizona (United States Geological Survey).

Arizona Department of Water Resources. 2009. Section 3.14 Willcox Basin. In Arizona Water Atlas, 534–602.

Beschta R, Pyles M, Skaugset A, Surfleet C. 2000. Peakflow responses to forest practices in the western cascades of Oregon, USA. *Journal of Hydrology* **233**: 102–120.

Beven K. 2004. Robert E. Horton's perceptual model of infiltration processes. *Hydrological Processes* **18**: 3447–3460.

Bosch JM, Hewlett JD. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology* **55**: 3–23.

Branson FA, Gifford GF, Renard KB, Hadley RF. 1981. Rangeland Hydrology, Soc. Rng. Mgmt., Rng. Sci. Ser *1*.

Brooks KN, Ffolliott PF, Gregersen HM, DeBano LF. 1997. *Hydrology and the Management of Watersheds*. Iowa State University Press: Ames, Iowa.

Brunner GW. 2002. HEC-RAS river analysis system. Hydraulic reference manual. Version 1.0. (US Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center).

Canfield HE, Goodrich DC. 2003. Studies of scale and processes in hydrologic modeling on the lucky hills watershed. In Proceedings of the First Interagency Conference on Research on the Watersheds, 444–450.

Castillo VM, Mosch WM, García CC, Barberá GG, Cano JAN, López-Bermúdez F. 2007. Effectiveness and geomorphological impacts of check dams for soil erosion control in a semiarid Mediterranean catchment: El Cárcavo (Murcia, Spain). CATENA, **70**(3): 416–427. DOI: 10.1016/j.catena.2006.11.009

Castillo C, Pérez R, Gómez JA. 2013. A conceptual model of check dam hydraulics for gully control. *Hydrology & Earth System Sciences Discussions* **10**(9).

Dalrymple T, Benson MA. 1967. Measurement of peak discharge by the slope-area method; Chapter A2. In *U.S. Geological Survey Techniques of Water-Resources Investigations*, U.S. Geological Survey: Denver, CO 80225, 12.

DeBano LF, Heede BH. 1987. Enhancement of riperian ecosystems with channel structures. *JAWRA Journal of the American Water Resources Association* **23**: 463–470.

Dobie K. 2012. An amateur rancher brings the wastelands of the Southwest back to life. Oprah.

Doolittle WE. 1985. The use of check dams for protecting downstream agricultural lands in the prehistoric southwest: a contextual analysis. *Journal of Anthropological Research* **41**: 279–305.

Du Bray EA, Pallister JS. 1991. An ash flow caldera in cross section: ongoing field and geochemical studies of the mid-tertiary Turkey Creek caldera, Chiricahua Mountains, SE Arizona. *Journal of Geophysical Research, Solid Earth* **96**: 13435–13457.

Du Bray EA, Pallister JS. 1995. *Area Adjacent to the Turkey Creek Caldera*. Cochise County: Arizona.

Du Bray EA, Pallister JS. 1999. Recrystallization and anatexis along the plutonic-volcanic contact of the Turkey Creek caldera, Arizona. *Geological Society of America Bulletin* **111**: 143–153.

Fish SK, Fish PR, Varineau R, Villalpando E. 2013. In flight: Adriel Heisey's images of trincheras archaeology.

Fuller J. 2014. Cochise County ALERT system.

Goodrich DC, Schmugge TJ, Jackson TJ, Unkrich CL, Keefer TO, Parry R, Bach LB, Amer SA. 1994. Runoff simulation sensitivity to remotely sensed initial soil water content. *Water Resources Research* **30**: 1393–1405.

Goodrich DC, Faurès J-M, Woolhiser DA, Lane LJ, Sorooshian S. 1995. Measurement and analysis of small-scale convective storm rainfall variability. *Journal of Hydrology* **173**: 283–308.

Goodrich DC, Lane LJ, Shillito RM, Miller SN, Syed KH, Woolhiser DA. 1997. Linearity of basin response as a function of scale in a semiarid watershed. *Water Resources Research* **33**: 2951–2965.

Graham J. 2009. *Chiricahua National Monument Geologic Resources Inventory Report* National Park Service: Denver, Colorado.

Halvorson WL, Thomas K, Graham L, Kunzmann MR, Bennett PS, Van Riper C, Drost C. 2002. *The Arizona GAP Analysis Project Final Report*. US Geological Survey, Biological Resources Division, Western Ecological Research Center, University of Arizona: Tucson, AZ; 166.

Heede BH. 1977. Case study of a watershed rehabilitation project : Alkali Creek, Colorado / ([Fort Collins, Colo.] : Dept. of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station.

Heede BH, DeBano LF. 1984. Gully rehabilitation—a three-stage process in a sodic soil. *Soil Science Society of America Journal* **48**: 1416–1422.

Hernandez M, Miller SN, Goodrich DC, Goff BF, Kepner WG, Edmonds CM, Jones KB. 2000. Modeling runoff response to land cover and rainfall spatial variability in semi-arid watersheds. In *Monitoring Ecological Condition in the Western United States*, Sandhu SS, Melzian BD, Long ER, Whitford WG, Walton BT (eds). Springer: Netherlands; 285–298.

Herold LC. 1965. *Trincheras and Physical Environment Along the Rio Gavilan, Chihuahua, Mexico* Department of Geography: University of Denver.

Hornbeck JW. 1973. The problem of extreme events in paired-watershed studies.

Huang M, Zhang L, Gallichand J. 2003. Runoff responses to afforestation in a watershed of the Loess Plateau, China. *Hydrological Processes* **17**: 2599–2609.

Juracek KE. 1999. Estimation of potential runoff contributing areas in Kansas using topographic and soil information. U.S. Geological Survey Water-Resources Investigations Report *994242*, 29.

Kennedy J, Goodrich D, Unkrich C. 2013. Using the KINEROS2 modeling framework to evaluate the increase in storm runoff from residential development in a semiarid environment. *Journal of Hydrologic Engineering* **18**: 698–706.

Kincaid DR, Osborn HB, Gardner JL. 1966. Use of unit-source watersheds for hydrologic investigations in the semiarid Southwest. *Water Resources Research* **2**: 381–392.

Kreyszig E. 1993. *Advanced Engineering Mathematics* John Wiley and Sons, Inc.: New York.

Lee AJ, Ferguson RI. 2002. Velocity and flow resistance in step-pool streams. *Geomorphology* **46**: 59–71.

Lenzi MA. 2002. Stream bed stabilization using boulder check dams that mimic step-pool morphology features in Northern Italy. *Geomorphology* **45**: 243–260.

Malcom JW, Radke WR. 2008. Effects of riparian and wetland restoration on an avian community in southeast Arizona, USA. *Open Conservation Biology Journal* **2**: 30–36.

Marjaniemi DK. 1969. Geologic history of an ash-flow sequence and its source area in the Basin and Range Province of southeastern Arizona. Thesis, University of Arizona: Tucson, Arizona.

Martín-Rosales W, Gisbert J, Pulido-Bosch A, Vallejos A, Fernández-Cortés A. 2007. Estimating groundwater recharge induced by engineering systems in a semiarid area (southeastern Spain). *Environmental Geology* **52**: 985–995.

Milzow C, Molnar P, McArdell B, Burlando P. 2004. The step-pool morphology of a steep mountain stream. Unpublished Thesis, Eidgenössische Technische Hochschule Zurich.

Minckley WL. 1998. Ecosystem repair by headwater erosion control: West Turkey Creek, Chiricahua Mountains, Arizona (Clark Foundation).

Nichols MH, McReynolds K, Reed C. 2012. Short-term soil moisture response to low-tech erosion control structures in a semiarid rangeland. *CATENA* **98**: 104–109.

Norman LM, Levick LR, Guertin DP, Callegary JB, Quintanar Guadarrama J, Zulema Gil Anaya C, Prichard A, Gray F, Castellanos E, Tepezano E, Huth H, Vandervoet P, Rodriguez S, Nunex J, Atwood D, Patricio Olivero Granillo G, Octavio Gastelum Ceballos F 2010. Nogales flood detention study. *U.S. Geological Survey Open-File Report* **2010-1262**: 112.

Norman LM, Villarreal ML, Pulliam HR, Minckley R, Gass L, Tolle C, Coe M. 2014. Remote sensing analysis of riparian vegetation response to desert marsh restoration in the Mexican Highlands. *Ecological Engineering* **70C**: 241–254.

Omernik JM. 1987. Ecoregions of the conterminous United States. *Annals of the Association of American Geographers* **77**: 118–125.

Osborn HB, Lane L. 1969. Precipitation-runoff relations for very small semiarid rangeland watersheds. *Water Resources Research* **5**: 419–425.

Pandey DN, Gupta AK, Anderson DM. 2003. Rainwater harvesting as an adaptation to climate change. *Current Science* **85** (1): 46–59.

Perlman H. 2014. How streamflow is measured.

Polyakov VO, Nichols MH, McClaran MP, Nearing MA. 2014. Effect of check dams on runoff, sediment yield, and retention on small semiarid watersheds. *Journal of Soil and Water Conservation* **69**: 414–421.

Radke WR. 2013. National wildlife refuge management on the United States/Mexico border.

Skroch M. 2008. Sky islands of North America: a globally unique and threatened inland archipelago : articles : terrain.org. A journal of the built & natural environments, *Islands & Archipelagos* **69**: 147–152.

Smith CF, Cordova JT, Wiele SM. 2010. The continuous slope-area method for computing event hydrographs (United States Geological Survey).

Stabler DF. 1985. Increasing summer flow in small streams through management of riparian areas and adjacent vegetation: a synthesis. Johnson

RR, Ziebell CD, Patton DR, Ffolliott PF, and Hamre RH (technical Coordinators), *Riparian Ecosystems and Their Management: Reconciling Conflicting Uses*. United States Department of Agriculture, Forest Service, General Technical Report RM-120 206–210.

Stewart AM, Callegary JB, Smith CF, Gupta HV, Leenhouts JM, Fritzinger RA. 2012. Use of the continuous slope-area method to estimate runoff in a network of ephemeral channels, southeast Arizona, USA. *Journal of Hydrology* **472–473**: 148–158.

Turnipseed DP, Sauer VB. 2010. Discharge measurements at gaging stations. In *U.S. Geological Survey Techniques and Methods*, U.S. Geological Survey: Reston, Virginia; 87.

U.S. Geological Survey. 1990. National water summary 1987-hydrologic events and water supply and use: U.S. Geological Survey Water-Supply Paper 2350, 553.

Van Loben Sels RC, Congdon JD, Austin JT. 1997. Life history and ecology of the Sonoran mud turtle (Kinosternon sonoriense) in southeastern Arizona: a preliminary report. *Chelonian Conservation and Biology* **2**: 338–344.

Veum KS, Goyne KW, Motavalli PP, Udawatta RP. 2009. Runoff and dissolved organic carbon loss from a paired-watershed study of three adjacent agricultural watersheds. *Agriculture, Ecosystems & Environment* **130**: 115–122.

Voeltz J. 2010. El Coronado Ranch; collaborative conservation on private lands. *Eddies* **3**: 24–29.

Warshall P. (1995). The Madrean Sky Island Archipelago: a planetary overview. In DeBano LH, Ffolliott PH, Ortega-Rubio A, Gottfried GJ, Hamre RH, Edminster CB, Tech. Coords. *Biodiversity and Management of the Madrean Archipelago: The Sky Islands of Southwestern United States and Northwestern Mexico*. 1994 Sept. 19-23; Tucson, AZ, U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station: Fort Collins, CO; 6–18.

Waterfall P. 2004. Harvesting rainwater for landscape use. Available online: http://arizona.openrepository.com/arizona/handle/10150/144824.

Wilm HG. 1949. How long should experimental watersheds be calibrated? *Transactions, American Geophysical Union* **30**: 272. DOI: 10.1029/TR030i002p00272

Ziemer RR, Ryan DF. 2000. Current status of experimental paired-watershed research in the USDA Forest Service. In 2000 Fall Meeting, (San Francisco, Calif.).