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ABSTRACT: In northwestern Mexico and the southwestern United States, limited water supplies and fragile landscapes jeopardize world-renowned biological diversity. Simple rock detention structures have been used to manage agricultural water for over a thousand years and are now being installed to restore ecohydrological functionality but with little scientific evidence of their success. The impacts, design, and construction of such structures has been debated among local restoration practitioners, management, and permitting agencies. This article presents archeological documentation, local contentions, and examples of available research assessments of rock detention structures in the Madrean Archipelago Ecoregion. A US Geological Survey study to quantify impacts of rock detention structures using remote-sensing analyses, hydrologic monitoring, vegetation surveys, and watershed modeling is discussed, and results rendered in terms of the critical restoration ecosystem services provided. This framework provides a means for comparing management actions that might directly or indirectly impact human populations and assessing tradeoffs between them.

RESUMEN: En el noroeste de México y suroeste de los Estados Unidos, las reservas limitadas de agua y los paisajes frágiles ponen en peligro la mundialmente reconocida diversidad biológica. Las estructuras sencillas de detención de rocas se han utilizado para manejar agua de uso agrícola desde hace más de mil años y ahora se están instalando para restaurar la funcionalidad ecohidrológica, aunque con poca evidencia científica de su éxito. Los impactos, el diseño y la construcción de dichas estructuras se han debatido entre profesionales locales de restauración, gestores y agencias de expedición de permisos. Este artículo presenta documentación arqueológica, contenciones locales y ejemplos de evaluaciones de investigación disponibles de estructuras de detención de rocas en la ecorregión del archipiélago Madrense. Se analiza un estudio del Servicio Geológico de Estados Unidos para cuantificar los impactos de las estructuras de detención de rocas utilizando análisis de detección remota, monitoreo hidrológico, estudios de vegetación y modelado de cuencas hidrográficas y los resultados se exponen en términos de los servicios críticos de restauración de ecosistemas proporcionados. Este marco proporciona un medio para comparar las acciones de gestión que podrían afectar directa o indirectamente a las poblaciones humanas y para evaluar las compensaciones entre ellas.

KEYWORDS: Riparian restoration, erosion-control structures, ecohydrology, ecosystem services, aridlands

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Introduction

Human settlements and land-use practices have resulted in habitat degradation and the loss of biodiversity in the United States-Mexico borderlands.[1] These arid and semiarid landscapes have recently been subject to a multidecadal drought, with repercussions still looming related to climate.[2,3] And, as populations grow, resources become more imperiled and depleted.[4-6] Watershed restoration projects attempt to bring ecosystems back to natural conditions, although this can be challenging, given the dynamic nature of ecosystems.[7] As the term "restoration" itself can be ambiguous due to varied interpretations, the term ecological restoration is defined here as intentional action to help ecosystems recover.[8] Stakeholder and economic support is tied to the success of ecological restoration projects.[6] In return, restoration projects can provide measurable benefits to people, which is known as ecosystem services.[7] Predegradation conditions are largely unknown globally and hence, restoration practitioners are encouraged to overcompensate accommodations of both biodiversity and ecosystem services.[9] This idea has further evolved to include changes in response to altered climate.[10,11] There is a demand for applied environmental science that can be used to form markets in restoration ecosystems services.[12]

Global water availability may be one facet of the environment not yet being properly accounted for economically. For example, the number of river restoration projects in the United States is increasing with estimated expense of over $1 billion annually.[13,14] However, there is a disconnect between river restoration, water availability, and social value in the United States because most citizens have access to potable water.[15] While drinking water supplies are critical, the restoration of natural water sources provides a larger assemblage of benefits to be considered. Rivers themselves are highly valued by the public,[16,17] especially in aridlands. Ecological systems, such as desert riparian areas, are particularly threatened and are in need of conservation action.[18] These ephemeral and intermittent streams provide many direct and indirect landscape-hydrologic connections.[19] Previous researchers have indicated that river restoration assists the establishment of improved biophysical processes in degraded waterways and should be

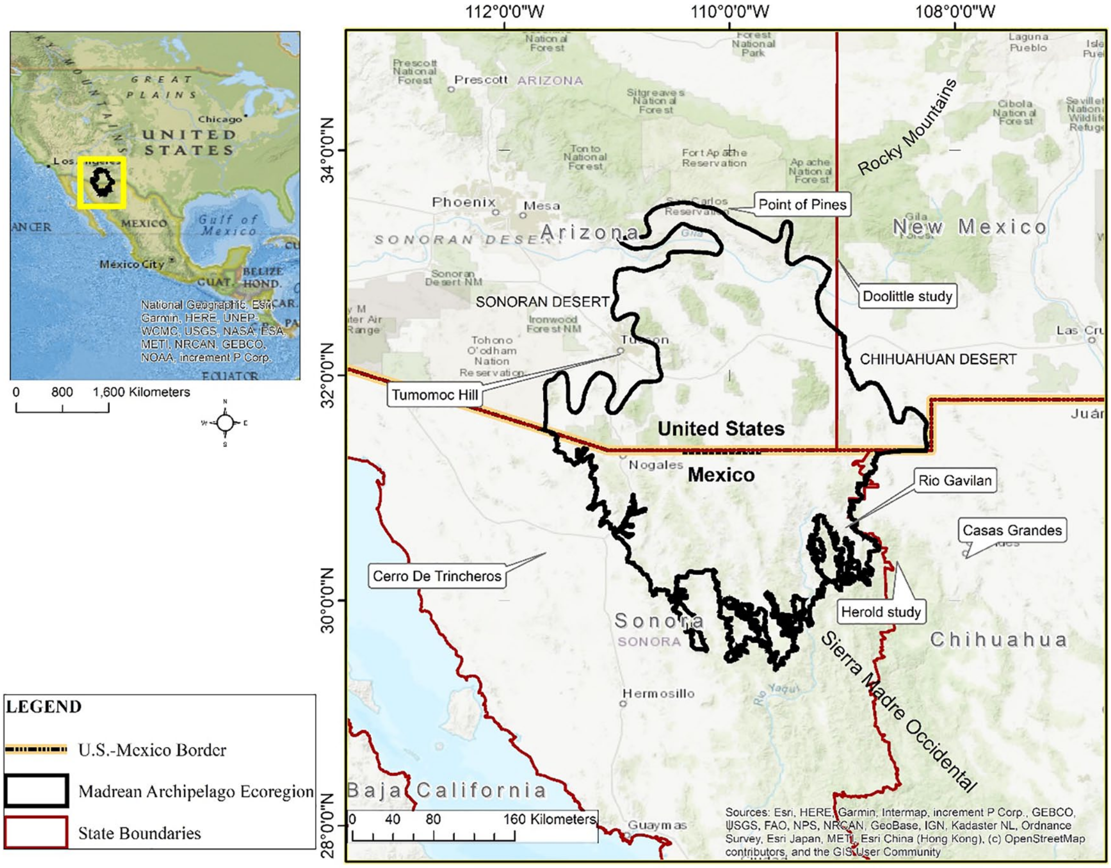

Figure 1. Location map portraying the Madrean Archipelago Ecoregion in relationship to states, countries, and surrounding deserts and mountain ranges with reference to pre-Columbian structures.

designed and informed by geomorphic, hydrological, and ecological theory.[16,20] In this article, restoration of arid and semiarid stream functionality is framed in terms of providing ecosystem services.

In the Madrean Archipelago Ecoregion of the United States-Mexico border, people have installed rock detention structures (RDS) for thousands of years to control water for agriculture. Most recently, restoration practitioners have been installing RDS to increase water availability, promote vegetation, and decrease erosion, but with limited scientific evidence of their success. Practitioners, managers, and policymakers often disagree about the validity and efficacy of different approaches and permitting restrictions hinder construction.[16] Some outdated and conflicting perceptions further retard practice.

The goal of this article is to summarize the history and application of RDS in the Madrean Archipelago Ecoregion and encapsulate over 5 years of multidisciplinary research and findings to provide new understanding and strategies to valuate outcomes that could assist arid and semiarid land- and water-resource managers and policymakers. Specifically, this article presents an overview of riparian restoration, historical water, and land management practices as well as current practices and opinions pertaining to RDS. Examples of available existing research assessments are also summarized. Finally, current research being conducted by the U.S. Geological Survey (USGS) designed to build the science of restoration ecology in response to the installation of RDS is discussed with results portrayed in terms of the ecosystem services that RDS provide.

Study Area and Background

The Madrean Archipelago Ecoregion is characterized by isolated forested mountain ranges, or "Sky Islands," surrounded by a "Sea" of deserts and grasslands, situated along the international border of United States-Mexico (Figure 1). Annual precipitation in the low-elevation desert scrub is ~100 mm and ~800 mm in mountain peaks, half of which occurs as high-intensity events (July-September), creating overland flow and impacting surface conditions. Surface runoff flows into streams that are mostly intermittent or ephemeral, and when laden with sediment, can reduce water quality.[19,21] Arroyo cutting and gullying are noted regionally to be increasing since the latter part of the 19th century.[22] Communities of riparian vegetation occupy floodplains adjacent to streams where the water table is near the surface most of the year.[23] The condition of these networks is dependent on movement and storage of sediments through the channel systems.[23] Riparian vegetation reduces velocity of overland flow, captures sediments and other pollutants from hill slopes, and further maintains bank stability

Table 1. Types of rock detention structures and their descriptions.

RDS	DESCRIPTION
Riprap, Armor, Spreaders, and *Trincheras*	Loose stones placed adjacently to slow water on hill slopes (often used to form "aprons" below larger RDS)
One-rock dam	A single layer of rock on the bed of a channel
Check dam or gully plug	A stack of loose rocks, that does not exceed ~1 m
Gabion	A cage of fence material filled with rocks and usually keyed into bedrock of larger channels, and sometimes stacked upon each other (reinforced check dam)

Abbreviation: RDS, rock detention structure.

Figure 2. A massive ca. 2000-year-old Native American trinchera feature (built-up rock terrace) near the crown of Tumamoc Hill, Arizona.[37]

and channel integrity.[23] Groundwater withdrawals can reduce surface flows and compromise dependent processes.[24] Overgrazing, fire suppression, and weather extremes (drought and high-intensity rain) have led to ecoregion-wide watershed degradation.[24] In the early 1990s, hydrologists identified a need for better understanding of the fundamental hydrologic processes and soil-vegetation relationships responsible for sustaining landscape stability in the ecoregion.[24]

Rock detention structures are being used to restore the ecohydrology of ephemeral stream channels, with goals of reducing stream flow velocity, limiting erosion, retaining sediment, and promoting surface-water infiltration for vegetation growth and habitat provisioning.[25] There are many types of RDS being used (Table 1), with selections dependent on size, location, design configuration, and preferred materials. Variation in objectives (ie, water harvesting, floodplain connection, agriculture promotion, grade-control, erosion-control, and gully-control) often determine RDS design, as described in handbooks available for practitioners interested in installing RDS.[26-30] Here, the focus is on commonality among RDS, that is, they are composed primarily of rock material and are installed to detain water for a short period of time rather than retain water permanently.

Pre-Columbian structures

Archeologists have qualitatively identified some functions of RDS in the ecoregion over time. *Trincheras*, dating from 1250 BCE to CE 1450, are prehistoric terraces with rock retaining walls used for various functions including habitation, ceremonial purposes, defense refuges, and related to early forms of irrigating agriculture (Figures 1 and 2).[31-36] Classification of *trincheras* for agricultural sites includes: (1) "terraces" (check dams) built as low walls across small stream channels to hold soil and cause flowing water to soak in rather than runoff, and (2) "linear borders" (riprap) built as alignments of stones along gentle slopes to reduce soil erosion, slow runoff, and increase infiltration for agricultural purposes.[36]

Archeological evidence indicates that check dams were installed in southwestern New Mexican mountains to reduce high flows and sedimentation to a *cienega*, or desert wetland, located downstream, that was likely cultivated in prehistoric times (CE 750-1150).[38,39] While organic soils were found to be stored behind these RDS, they were documented as having dissipated energy and increased residence time of water, thus reducing sedimentation in ponds downstream and reducing erosion and gullying upstream.[39] The Point of Pines area was occupied from 2000 BCE to CE 1450, with evidence of RDS built in 1000 (CE),[36] and *trincheras* dating back to 1100 to 1450 (CE) have been studied in northwestern Chihuahua, Mexico.[33] These sites were found to have low organic matter in soils stored behind ancient *trincheras* (deficient in both potassium and phosphorous); the larger structures that lacked engineering had failed over time, but those properly keyed into bedrock and/or smaller structures, appeared relatively stable up to 600 years later.[33] *Trincheras* found in the Sierra Madre Occidental Mountains irrigated the downstream floodplain by increasing runoff.[32] The cost of construction was considered low in terms of labor, especially compared to the benefits received.[31,37,39] While these archeological notes provide anecdotal evidence of some benefits of RDS, which are the basis of current practice, they are not scientifically proven.

Restoration practitioners (advocates and critics)

Despite common goals and mutual interest in watershed restoration using RDS in the Madrean Archipelago Ecoregion, there is a lack of consensus regarding the type of structure to use. Contention about flaws in design and approach creates a demand for empirical evidence to resolve which RDS design is appropriate for restoration purposes. Following is a description of some locally cited practices and diverse practitioner opinions.

Natural channel design (NCD)[40,41] is a framework for stream and river restoration, introduced in the 1990s. Use of the NCD approach is often required by regulatory agencies issuing stream permits;[42] however, some oppose the NCD approach for use in stream restoration, suggesting it may oversimplify complex fluvial processes and channel response.[13,43,44] It should be noted, however, that little data are available to resolve these contentions.[13] While careful responses to critics have been documented with information on the proper use and/or abuse of NCD methods for river restoration,[45,46] there continues to be a need for scientific analysis and data to improve restoration design and application.[46] In the desert Southwest, many use the NCD approach in the design, construction, and management of various riparian restoration projects. Those opposed to the NCD approach promote induced meandering to restore natural stream processes using various structures, properly sized and strategically placed, based on the size of the channel, survey, design, and magnitudes of expected flood events.[27] Critics suggest that sinuosity of a stream cannot be forced as evidenced by a river's natural inclination to develop chute channels or meander cutoffs.[47]

Beginning in the mid-1980s, check dams, gabions, and *trincheras* were installed in what is now ~800 km^2 of private landholdings on either side of the United States-Mexico border to enhance wildlife habitat.[48,49] Qualitative observations of additional benefits of these RDS were documented, including soil and organic materials storage, reduction of flashy runoff, and increased groundwater retention reflected in longer flow durations.[50] However, use of these RDS was not without its critics. Induced-meander practitioners condemned the use of check dams as being expensive and ineffective,[41] suggesting they do not restore natural rivers and will ultimately fail.[27] State agencies contested use of gabions and earthen berms for lack of permitting, not putting public waters to beneficial use, and for creating dams that were too large with excessive storage capacity.[51] Use of gabions have also been commonly criticized for their potential to breach and fail in channels, allowing rock waste and wire caging to disperse downstream.[52]

Finally, multiple nonprofit organizations have worked with agencies, landowners, and volunteers in the Madrean Archipelago Ecoregion to restore ecosystems using a variety of RDS to restore physical processes and to train communities and volunteers in how to install low-technology RDS in many locations within the ecoregion.[53,54] Ultimately, as numerous opinions and beliefs exist about which types of RDS may or may not be appropriate for use in the ecoregion with little scientific evidence to resolve the issue, restoration efforts by managers, consulting agencies, and non-profit groups have been subject to trial and error in the field. Riparian ecological restoration activities that lack hypothesis development and testing, have few common metrics to evaluate success.[20,55] Most of these efforts have not been monitored, documented, tested, or formally quantified through field research or scientific study, and so there is a scientific-knowledge gap in RDS efficacy for restoration purposes.

Examples of existing scientific assessments

Researchers at the US Forest Service (USFS) used gully-control structures (check dams) in the Colorado Front Range in the 1960s, documenting benefits of erosion control and water quality improvements both on-site and downstream.[56] Other USFS studies describe earthen dams and dike spreaders, loose-rock and hand-placed-rock spreaders, and rock-rubble gully-control structures that were emplaced but breached not long after construction; however, their presence did improve vegetation cover and helped to slow and disperse the flow of water.[57] Low dams and barriers have been documented by the USFS to impact sedimentation depending on particle-size distribution and availability of material.[58] While positive impacts of these RDS on streamflow hydraulics, sedimentation, and riparian zone establishment were documented, they could also be destructive.[59] As a result, scientists suggested that the complexity of riparian ecosystems requires a multidisciplinary approach to evaluate impacts of channel structures.[59]

Research hydraulic engineers with the US Department of Agriculture's Agricultural Research Service (USDA-ARS) have been studying watershed restoration using low-technology rock check dams for the past 15 years in the ecoregion.[60-63] They have constructed, instrumented, and monitored multiple sets of rock check dams in southeastern Arizona, documenting capacity for sediment retention and a reduction in channel gradient.[60] Although researchers documented an initial postconstruction decrease in runoff from small rainstorms,[61,63] this response was not persistent.[64] More recently, working with the USGS and others, there has been an effort to catalog the occurrence of existing earthen berms and identify their potential to impact the geomorphology of a watershed over time.[65]

Research geomorphologists, hydrologists, and scientists at the USGS have been studying the impacts of RDS for more than 25 years in the desert Southwest. At a watershed rehabilitation project on the Zuni Reservation, New Mexico, large structures (rock and earth) were documented to be mostly filled with sediment and breached over time whereas small structures (rock and brush) had breached to a lesser extent (20%).[22] In 1995, these researchers suggested that repeat surveying at selected gully cross-sections and RDS, as well as monitoring vegetation and sediment could increase knowledge regarding efficacy of structures. Despite these studies, there remain many unanswered questions regarding the impacts of RDS and their ability to sustain ecohydrological cycles.

USGS Aridland Water Harvesting Study

In 2013, the USGS initiated the Aridland Water Harvesting Study to quantify observations being made by practitioners and to improve understanding of ecohydrological impacts of

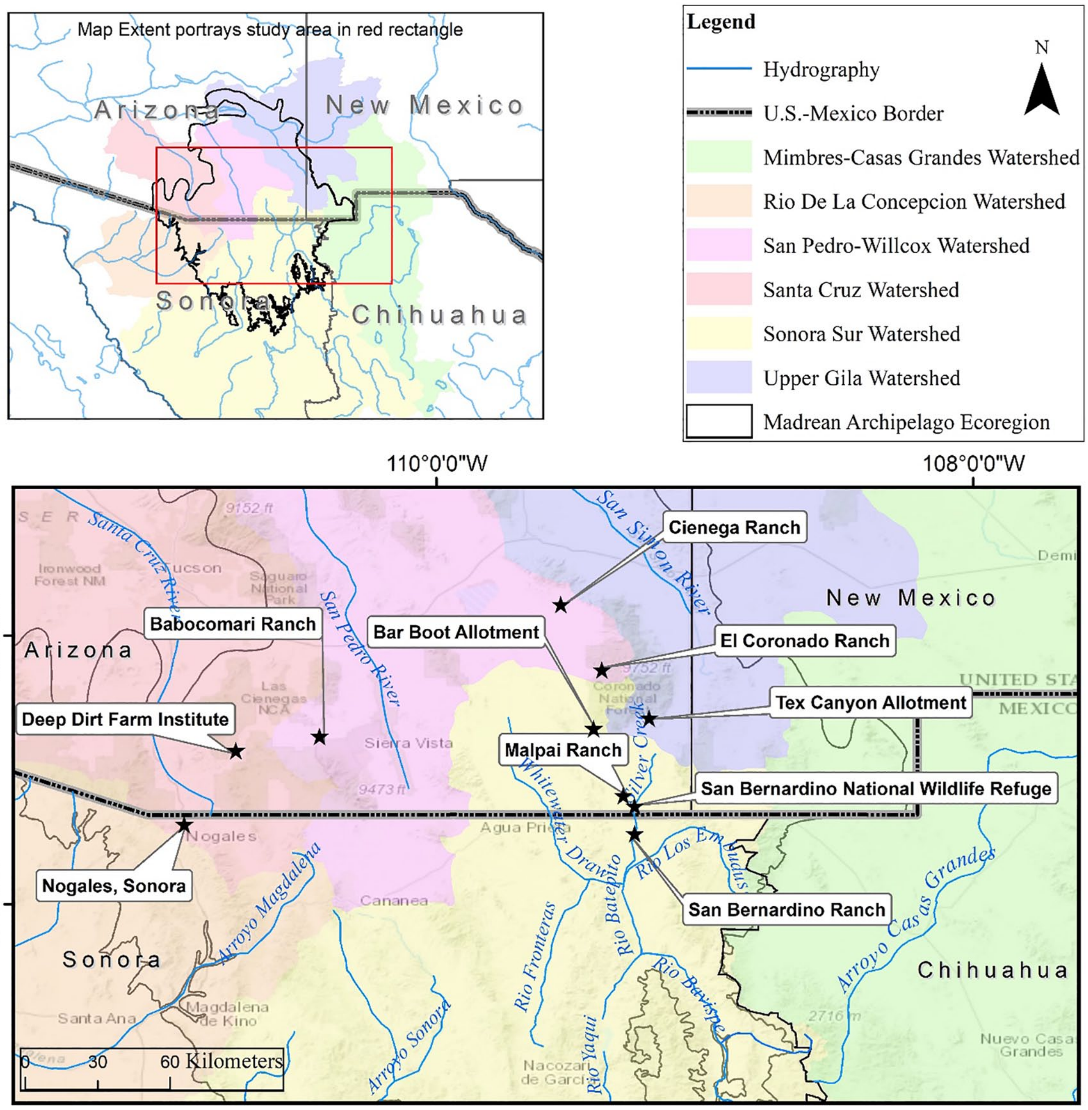

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Figure 3. Location map portraying Aridland Water Harvesting Study locations in relationship to hydrography, State and Federal boundaries, and watersheds in the United States-Mexico borderlands study area.

various RDS. The underlying goal of the research is to strengthen the ability to adapt ecosystems to changes in land use in the Madrean Archipelago Ecoregion (Figure 3). Adaptive management, guided by theory and experimentation (as opposed to trial and error), can aid the success of ecological restoration projects.[6,18,66] The Aridland Water Harvesting Study comprises multiple investigations examining potential ecosystem services of RDS, including large gabions (Figure 4),[28] check dams, and smaller rock dams (Figure 5). The research does not examine RDS installation, design, nor consistency, but does note the loose adherence of practitioners to follow specifications as defined in various guidebooks.[26-29]

This section summarizes published results of the Aridland Water Harvesting Study in relationship to the ecosystem services that RDS provide, including flood regulation; water regulation, purification, and provisioning; habitat provisioning; erosion regulation, carbon sequestration and storage; and social value in the Madrean Archipelago Ecoregion.

Flood regulation

In the cross-border urban environment of Nogales, Arizona, United States, and Nogales, Sonora, Mexico, known collectively as Ambos Nogales (Figure 3), flooding often exceeds channel capacity and adjacent land areas, endangering people. Working with colleagues from the USDA-ARS and others, the Kinematic Runoff and Erosion Model (KINEROS2) in the Automated Geospatial Watershed Assessment (AGWA) interface was used to assess flood vulnerability by quantifying volumes of runoff and peak flow, given various land-use scenarios.[68] Results portrayed flood-prone areas that might be appropriate for management intervention.[69] With support from the International Boundary and Water Commission, the model was further

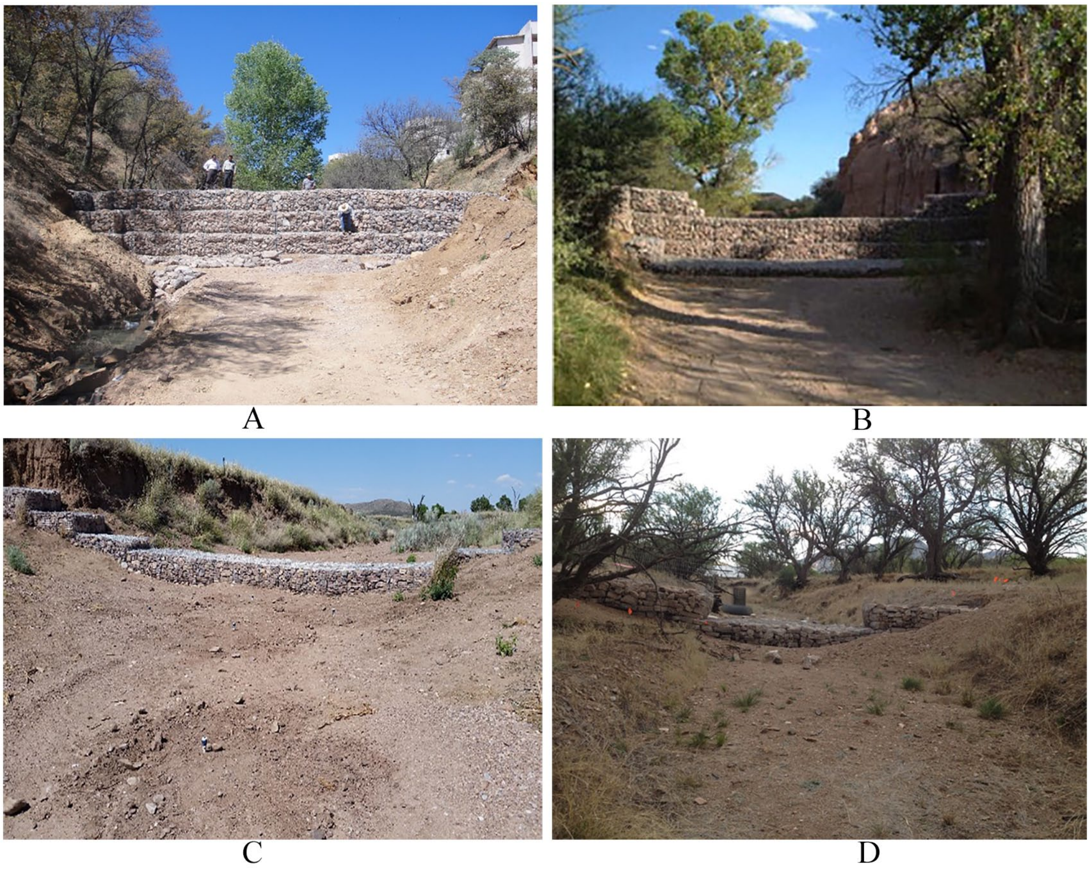


Figure 4. (A) Looking downstream at Cinco de Febrero, which experiences major flooding during monsoons, in Nogales, Sonora, Mexico (photo by Hans Huth [April 12, 2010]); (B) Gabion in Hay Hollow at Rancho San Bernardino, Sonora, Mexico (by Josiah Austin [October 27, 2001])[67]; (C) Gabion in Vaughn Canyon on the Babacomari Ranch (by James Callegary June 19, 2015); and (D) Gabion installed at Bone Creek on the Deep Dirt Farm Institute (by Kate Tirion (2014). See Figure 3 for map locations.

implemented to predict the capacity of suggested gabions under various flood and urbanization scenarios (Figure 4(A)). The model predicted that some of the intended gabions would reduce peak flows in small rainfall events (ie, 10 year, 1-h storm event) but would have little impact for larger storm flows (ie, 100 year, 6-h storm event). Conversely, other gabions were predicted to have little impact from either small- or large-sized storms, depending on location, upstream contributing source area, soil, slope, and so on (Figure 6).[69] The potential for RDS to regulate flood events and help reduce hazards was documented, and structures were installed at recommended locations around Nogales, Sonora, Mexico. This work also demonstrated the additional potential for gabions to capture large amounts of sediment regardless of storm size and highlighted the need for regular maintenance therein.[70]

Habitat provisioning

Multiple studies that address the potential for RDS to maintain and improve riparian vegetation and water availability have been documented, laying the groundwork for habitation. At *Cienega* San Bernardino, spanning the Arizona-Sonora border, gabion structures were installed by the US Fish and Wildlife Service at San Bernardino National Wildlife Refuge (SBNWR) and by the Cuenca los Ojos (CLO) Foundation over the course of 20+ years to restore surface water for native fishes (Figures 3 and 4(B)). *Cienegas*, or desert wetlands, are biodiverse yet sensitive habitats imperiled by demands for water and by changing climates.[18] A remote-sensing analysis, coupled with field data, was conducted to document impacts of gabion installation over time. Using a vegetation index (ie, Normalized Difference Vegetation Index; NDVI), health and plant biomass were quantified to compare gabion and control sites over a 27-year period. Results portray live green vegetation present at most sites treated by gabion installation and at a few of the control sites, where no gabions exist (Figure 7). Field sites established within the study area between 2000 and 2012 corroborate findings of established biomass at gabions. This research documented the potential to restore riparian vegetation using gabions with the implication of increased water availability, and further suggested the potential to alleviate drought conditions in a desert cienega.[67]

Additional analysis ensued to investigate spatial and temporal trends in vegetation greenness and soil moisture at Cienega San Bernardino. Results from this additional study confirmed higher greenness and vegetation water content levels, greater increases in greenness and water content through time, and a decoupling of vegetation greenness and water content from spring precipitation when compared to control sites in nearby

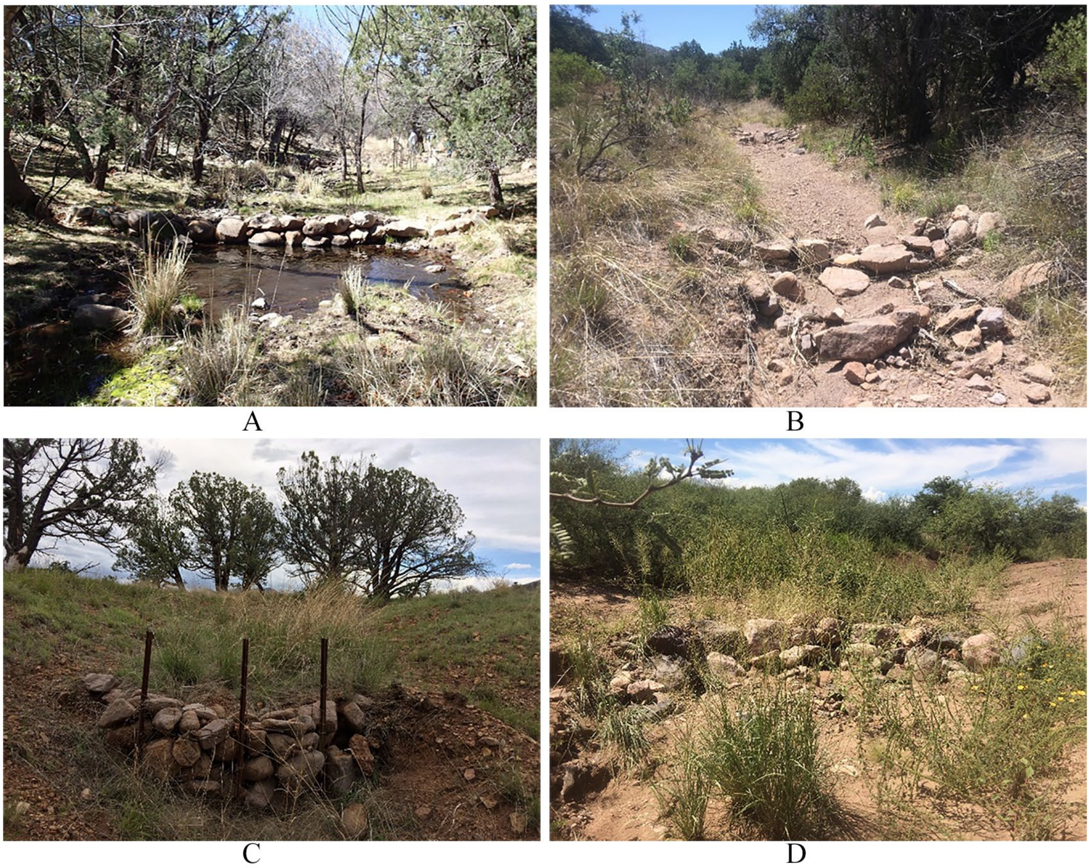


Figure 5. Photos of small structures at (A) Turkey Pen in the El Coronado Ranch, by Leila Gass, March 23, 2016)). (B) Bar Boot Allotment on the Douglas Ranger District, USFS; photo by Natalie R. Wilson, July 19, 2019)). (C) Tex Canyon on the Douglas Ranger District, USFS; photo by Natalie R. Wilson, July 14, 2015)). (D) Silver Creek on the Malpai Ranch, photo by Natalie R. Wilson (September 12, 2016). See Figure 3 for map locations.

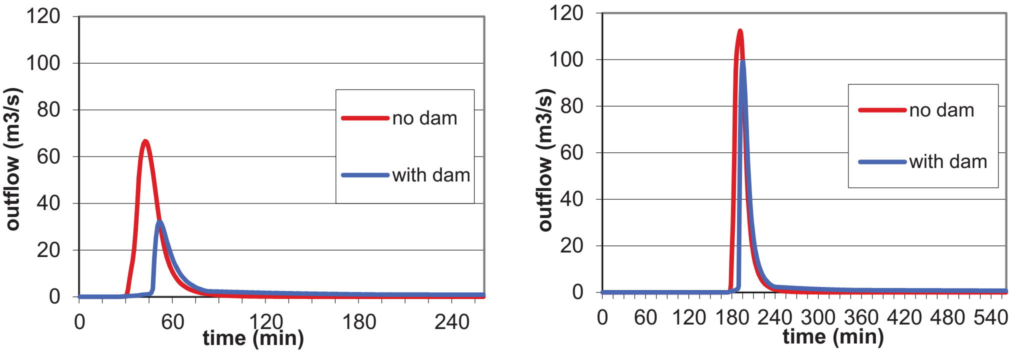


Figure 6. Gabion installation at the Cuesta Blanca subwatershed of Nogales, Sonora, Mexico, hydrograph results of modeling runoff response after a 10 year, 1-h storm event (left) and a larger 100 year, 6-h event (right)).[70]

tributary and upland areas (Figure 8).[71] This analysis documented the potential of gabions to increase live green vegetation, owing to increased water availability, at locations as far as 5 km downstream and 1 km upstream.[71]

A field study was launched in 2014 to monitor locations annually, during summer rainy seasons, to document on-the-ground measurements of vegetation abundance and species composition and changes that may not be observable using satellite imagery.[72] In the Chiricahua Mountains, the Sky Island Alliance, the Borderlands Restoration Network (BRN), the CLO Foundation and USFS partners installed and monitored small dams at the Bar Boot and Tex Canyon drainages (Figures 3, 5(B) and 5(C)).[53] In the Silver Creek drainage, the Bureau of Land Management contracted Stream Dynamics to install RDS in the Wildcat Draw tributary on the Malpai Ranch (Figures 3 and 5(D)). United States Geological Survey scientists partnered with these various practitioners and land managers to develop long- and short-term vegetation study plots to investigate vegetation changes over a 5-year period. Preliminary findings have indicated positive responses to RDS, with increases of perennial vegetation observed at most study sites.[72,73]

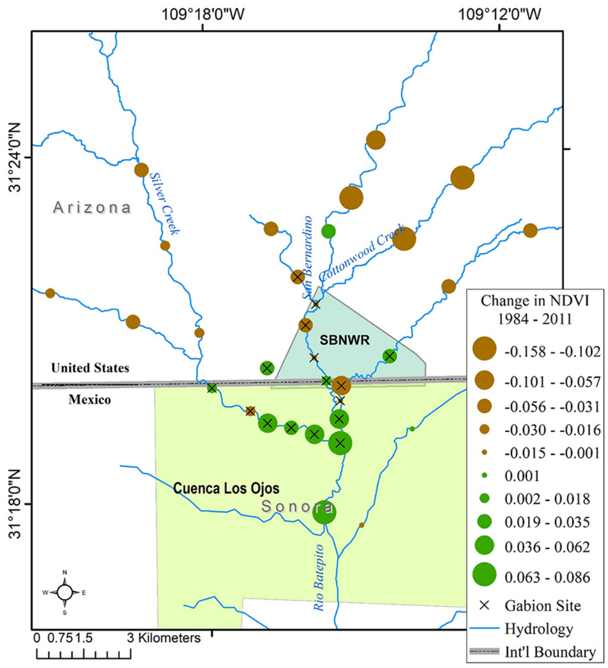


Figure 7. Map portrays results of 27 year satellite image analysis to track vegetation health at sites where gabions had been installed and comparing control sites (no gabions).[67]

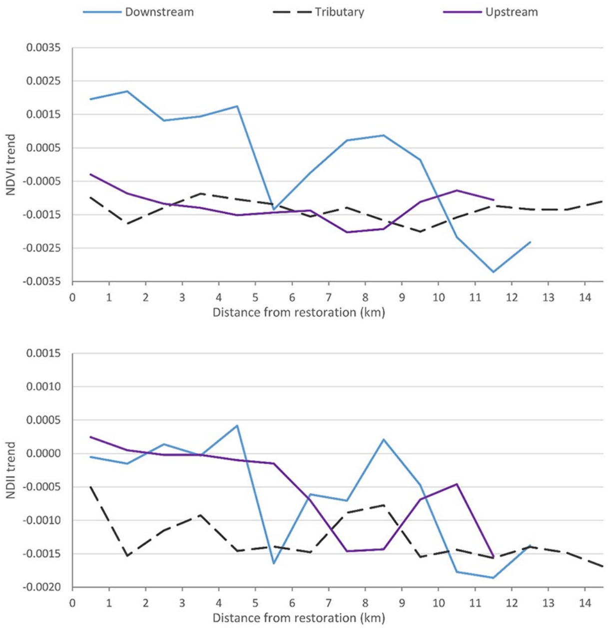


Figure 8. Graphs portray repeat analyses of the Normalized Difference Vegetation Index (NDVI; top) and new results from the Normalized Difference Infrared Index (NDII; bottom) accentuating impacts at distances from restoration sites, modified from Wilson and Norman.[71]

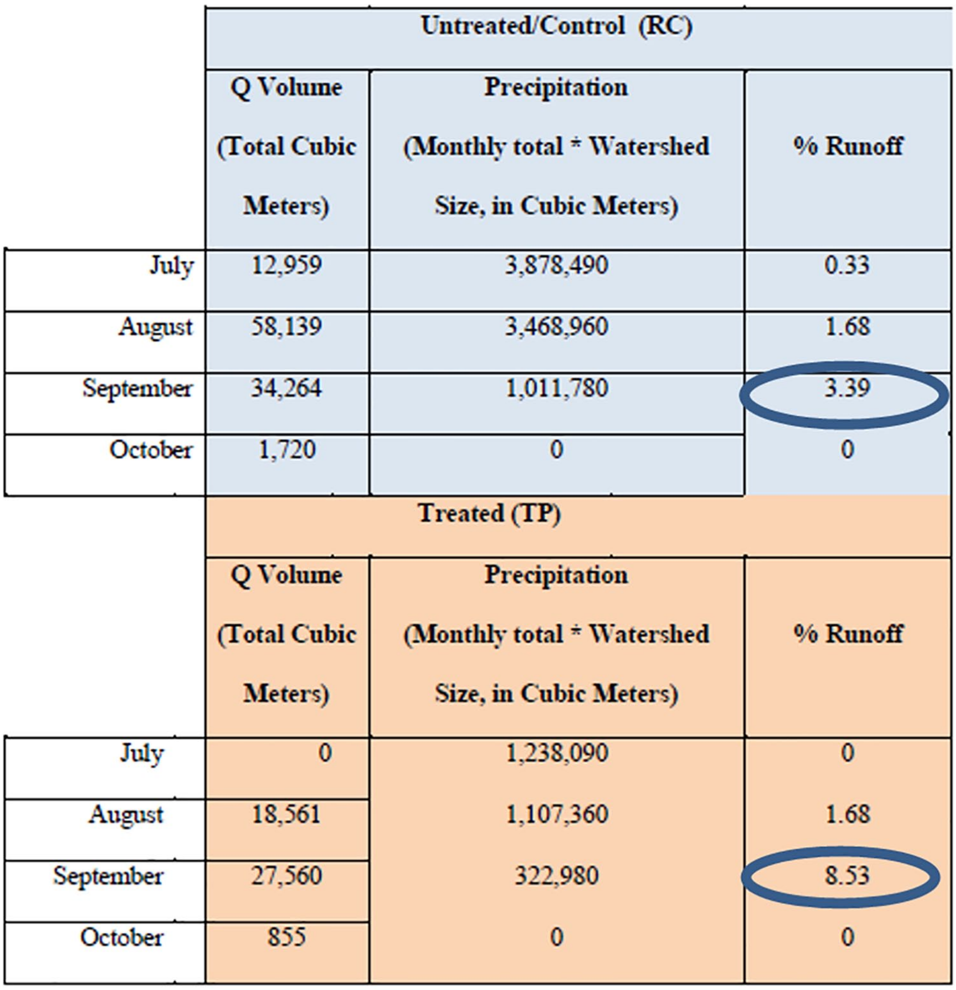
Water regulation, purification, and provisioning

The use of RDS through time to regulate water flow, improve water quality, and increase availability has been investigated at 2 ranches in the ecoregion study area. At the El Coronado Ranch, in the West Turkey Creek, Chiricahua Mountains, Arizona (Figure 3), one watershed had been extensively altered by the installation of thousands of small check dams over the course of 30 years (Figure 5(A)), while another had been left untreated (control). A paired-watershed approach was established to analyze the impacts of check dams on hydrologic function, given the adjacent location, similar land use, geology, vegetation, and precipitation. A new stream-gauging mechanism developed for remote areas, was modified and installed to measure discharge.[74,75] The watershed treated with check dams had a reduced runoff response to precipitation, especially noticeable in peak flows compared with the untreated watershed. At the beginning of the season, the runoff response to precipitation in the treated watershed was negligible, but over the course of the summer "monsoon," the response of the treated watershed increased to more than twice that of the untreated watershed, resulting in 28% more flow volume per area in the treated watershed compare to the untreated watershed (Figure 9). The cause for this delayed but increased response was hypothesized to be increased baseflow incurred from the RDS installed in arid and semiarid environments.[75] It was also noted that most of the check dams were still functional despite the age of construction.

At the Babocomari Ranch, in a tributary of the San Pedro River, southeastern Arizona (Figure 3), field experiments were coupled with surface and groundwater modeling to investigate using gabions to augment aquifer recharge (Figure 4(C)). Models were used to identify the best location to attempt recharge in an ephemeral channel, and field data were collected before and after gabions were installed by the BRN.[76] Downstream discharge measurements and a 3-dimensional computer model were used to calibrate a watershed model, simulate flow volumes, and extrapolate findings. In locations with gabions installed, average infiltration behind the gabions increased 10% compared to locations without gabions.[77] The average and high estimates of potential infiltration were used to alter hydraulic conductivity input to a watershed model to examine potential variations expected in the water budget, as a result of potential impacts from gabion installations (Figure 10).[76] Model results indicated a potential increase in lateral soil water incurred from gabion installation, as previously hypothesized at the El Coronado Ranch study.[75,76]

Erosion regulation

Multiple efforts were launched to investigate how RDS might reduce erosion rates, which is also directly related to water quality and site productivity. At the Deep Dirt Farm Institute (DDFI; Figure 3), a gabion was constructed by the BRN at the beginning of a 3-year study (Figure 4(D)). Runoff, sediment transport, and geomorphic modeling with repeat terrestrial laser scanner (TLS) surveys were used to map landscape change. Event-based runoff was initially estimated using KINEROS2 and then used as input to a 2-dimensional unsteady flow-and-sedimentation model (Nays2DH) that combined a gridded flow, transport, and bed and bank simulation with geomorphic change.[78] Figure 11 compares model-predicted elevation changes and survey-measured elevation changes following gabion



	Untreated/Control (RC)		
	Q Volume (Total Cubic Meters)	Precipitation (Monthly total * Watershed Size, in Cubic Meters)	% Runoff
July	12,959	3,878,490	0.33
August	58,139	3,468,960	1.68
September	34,264	1,011,780	3.39
October	1,720	0	0

	Treated (TP)		
	Q Volume (Total Cubic Meters)	Precipitation (Monthly total * Watershed Size, in Cubic Meters)	% Runoff
July	0	1,238,090	0
August	18,561	1,107,360	1.68
September	27,560	322,980	8.53
October	855	0	0

Figure 9. Rainfall-runoff response of stream treated with check dams veresus untreated in paired-watershed study.[75]

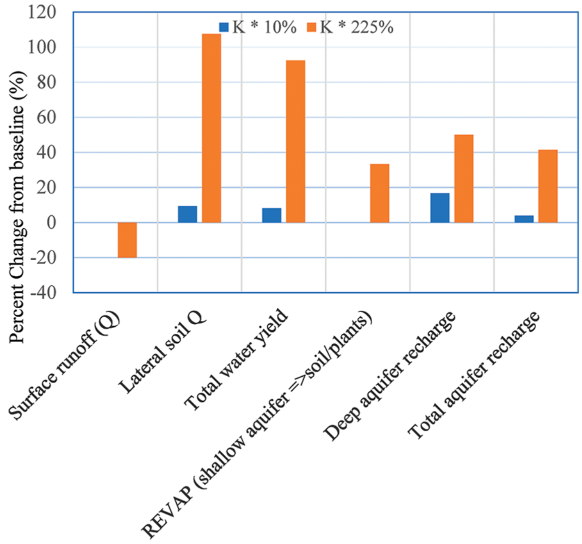


Figure 10. Chart portraying change predictions for the water budget in the future (2050) if gabions are installed throughout the watershed, where K = hydraulic conductivity.[76]

installation. Although the TLS survey measurements indicated greater elevation losses than that predicted by the model; both TLS and model results showed similar trends in elevation changes. Trend consistency between consecutive digital elevation model data acquisitions and uncalibrated simulations, demonstrated the potential to use models to predict hydraulics and approximate associated trends and patterns of aggradation and degradation resulting from gabions before they are installed.[25]

The effect of check dam infrastructure on soil conservation was also evaluated using the Soil and Water Assessment Tool (SWAT)[79] at the El Coronado Ranch. The SWAT model was calibrated for streamflow using the discharge documented during the summer of 2013[75] at the control site; the model was used to estimate sediment loads stored at the check dams in the treated watershed. Model results indicated approximately 630 tons of sediment was stored behind the check dams in the treated watershed upstream over a 3-year simulation period, which would likely have improved water quality downstream.[80] Additional characterization of the impacts of the check dams at El Coronado Ranch using geomorphic modeling and repeat TLS surveys to map landscape change further demonstrated the long-term effectiveness of the check dams and again, the potential utilization of modeling to quantify geomorphic change.[25]

Carbon sequestration and storage

A pilot study was initiated to evaluate stable isotope ratios of carbon and nitrogen at and around check dams at El Coronado

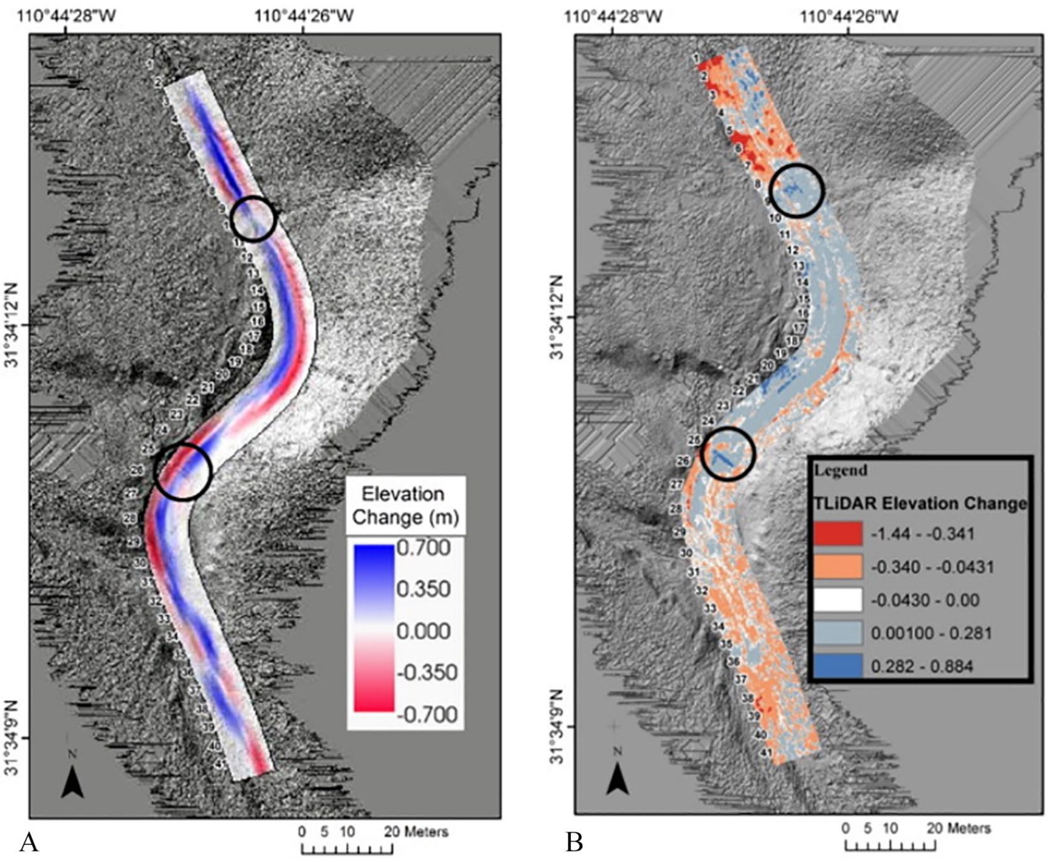


Figure 11. (A) Model results predict bedform shifts and geomorphology changes in the channel based on the installation of gabions, where measurements confirm accuracy of model predictions using and (B) terrestrial laser scanner surveys over a 3-year time period (before and after gabions were physically installed).[25]

Ranch. Results indicate the potential of check dams to increase carbon sequestration, especially in burned watersheds.[81] By extrapolating the results of the SWAT model simulation, which estimated increased sediment stored behind check dams over a 3-year period, with results from the isotopic analyses, researchers estimated approximately 16 to 17 tons of organic carbon could be sequestered by the check dams.[81] Further research to investigate how RDS might impact soil and vegetation carbon sequestration is warranted, especially given the potential to compensate practitioners if RDS can be used to offset emissions.[82]

Social value

Finally, a study was developed to identify spatial guidelines for restoration efforts. Partners in the BRN initiated a social survey to solicit perceived, nonmarket values related to restoration and conservation and provided it to the citizens in Sonoita Creek watershed, Arizona. The Social Values for Ecosystem Services (SolVES)[83] model, was applied to map survey responses across the watershed. Resulting maps indicated that citizen perception of benefits from the natural environment in this area focused on streams and the life-sustaining services, biological diversity, and aesthetics the watershed offers.[84] This research helped to highlight the perceived values of surface water in arid and semiarid lands. A similar effort is being developed at Ambos Nogales, United States-Mexico, to compare community preferences internationally.[85]

Study limitations

All of the ecohydrology studies described here may have inherent error in relationship to (1) the distribution and capture of rainfall, (2) unknown or variant groundwater conditions, and (3) the tools, methods, or scientists involved. In addition, the potential for materials other than soil to gather behind structures (eg, woody debris) was not considered in the studies described here but could contribute to results and hence, pose an avenue for further research. While it is recognizably difficult to establish parity between watersheds and between varied geography and ecology, and even more challenging to integrate variance in restoration approaches, it is absolutely critical to do so to move restoration practice, attitude, and policy forward.[13,43,86] Restoration ecohydrology science warrants continuous progression and copious rendition to validate findings and support the practice of ecological restoration. In addition to the ecosystem services described, the various techniques for monitoring the success of structures are offered as possible tools or methodologies useful for further investigation.

Conclusion

In arid and semiarid ecosystems, where water supplies are difficult to measure and anthropogenic footprints last a long time, studies to quantify the impacts of management practices on the greater ecohydrology are invaluable. The Madrean Archipelago Ecoregion has a well-documented history of RDS installed through time, yet little is known about their impacts on ephemeral streams or how new efforts might best use them. Holistic watershed management encompasses social, ecological, and hydrological systems, and sustainable feedback mechanisms. The management of installing RDS, including permitting, planning, and funding, is currently largely based on opinions, anecdotal evidence, perception about the impact of structures, and a general lack of scientific study. There is a need for unbiased scientific data to resolve these issues, educate land managers and inform policymakers regarding the use of RDS. Given the substantial financial investments being made in riparian and watershed restoration in the ecoregion, methodological rigor in qualitative and quantitative research to support actions and decision-making is imperative.[53]

This article describes the history of practice and the science related to installing RDS in the Madrean Archipelago Ecoregion as well as some associated misperceptions about RDS. The USGS Aridlands Water Harvesting Study comprises a variety of ecohydrological studies that have produced results supporting previous findings as well as providing new conclusions, understanding, strategies, and methods for monitoring structures. Study results have shown that RDS can be valuable to decrease peak flows associated with flood hazards.[69,70] They can increase surface-water availability in otherwise ephemeral streams of arid and semiarid lands, extending the duration of seasonal flow events and increasing flow volumes.[67,71,75] Rock detection structures can promote vegetation maintenance and health through drought, indicating increased water availability with positive effects extending up to 5 km downstream.[67,71,72] In some locations, 30-year-old structures are still functional for water and soil retention,[25,80] as well as carbon storage.[81] Social surveys indicate that people value the stream networks in their watershed and advocate for restoration.[84] Finally, studies have demonstrated that watershed models can be used for predictive-framework and decision-support.[25,69,70,76,80,87] These advances in restoration science, with science-based evidence that dispels prior assumptions, are being acknowledged by partner agencies who can revise management strategies[53,88] to help bridge the disconnect between restoration practice and the value of surface-water availability.

The prioritization of riparian restoration treatments or conservation investments is extremely important and can be facilitated by assessing possible tradeoffs among ecosystem services. One approach to safeguarding ephemeral riparian areas in the Madrean Archipelago Ecoregion may be through assessing some type of payment mechanism for ecosystem services or market-based incentives. For example, to offset footprints of groundwater pumping downstream through the investment of RDS installations to harvest rainwater. This article illustrates quantitative assessments of various RDS effects and benefits, yet the costs associated with collecting these different types of monitoring data have not yet been fully vetted. Future research to document costs of treatments and monitoring would be useful to researchers and practitioners aiming to continue this type of assessment. As more of the impacts of restoration using RDS are fully documented and valuated, effectively translating ecohydrological services into amounts of water that could be restored to arid or semiarid landscapes, it will be possible to account for RDS installation in water budgets, locally and regionally, and in market-based solutions that fund such projects.

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Supplemental Material

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REFERENCES

1. Gottfried G, Ffolliott PF, Gebow BS, Eskew LG, Collins LC. *Merging Science and Management in a Rapidly Changing World: Biodiversity and Management of the Madrean Archipelago III and 7th Conference on Research and Resource Management in the Southwestern Deserts; 2012 May 1-5; Tucson, AZ*. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station; 2013.
2. Yanahan AD, Moore W. Impacts of 21st-century climate change on montane habitat in the Madrean Sky Island Archipelago. *Divers Distrib*. 2019;25:1625-1638. doi:10.1111/ddi.12965.
3. Stahle DW. Anthropogenic megadrought. *Science*. 2020;368:238-239. doi:10.1126/science.abb6902.
4. Gleick PH. Global freshwater resources: soft-path solutions for the 21st century. *Science*. 2003;302:1524-1528. doi:10.1126/science.1089967.
5. Stocking MA. Tropical soils and food security: the next 50 years. *Science*. 2003;302:1356-1359. doi:10.1126/science.1088579.
6. Falk DA, Palmer MA, Zedler JB; Society for Ecological Restoration International, eds. *Foundations of Restoration Ecology*. Washington, DC: Island Press; 2006.
7. Breed MF, Lowe AJ, Mortimer PE. Restoration: "Garden of Eden" unrealistic. *Nature*. 2016;533:469-469. doi:10.1038/533469d.
8. Society for Ecological Restoration International, Science & Policy Working Group. The SER international primer on ecological restoration. https://www.ser-rrc.org/resource/the-ser-international-primer-on/. Published October 2004.
9. Gann GD, McDonald T, Walder B, et al. International principles and standards for the practice of ecological restoration. Second edition. *Restor Ecol*. 2019;27:S1-S46. doi:10.1111/rec.13035.
10. Falk DA. Restoration ecology, resilience, and the axes of change. *Ann Mo Bot Gard*. 2017;102:201-216. doi:10.3417/2017006.
11. Woodworth P. *Our Once and Future Planet: Restoring the World in the Climate Change Century*. Chicago, IL: The University of Chicago Press; 2015.
12. Palmer MA, Filoso S. Restoration of ecosystem services for environmental markets. *Science*. 2009;325:575-576. doi:10.1126/science.1172976.
13. Lave R. The controversy over natural channel design: substantive explanations and potential avenues for resolution. *JAWRA J Am Water Resour Assoc*. 2009;45:1519-1532. doi:10.1111/j.1752-1688.2009.00385.x.

14. Bernhardt ES, Palmer MA, Allan JD, et al. Synthesizing U.S. river restoration efforts. *Science*. 2005;308:636-637. doi:10.1126/science.1109769.
15. Nagle G. Evaluating “natural channel design” stream projects. *Hydrol Process*. 2007;21:2539-2545. doi:10.1002/hyp.6840.
16. Wohl E, Angermeier PL, Bledsoe B, et al. River restoration: OPINION. *Water Resour Res*. 2005;41:W10301. doi:10.1029/2005WR003985.
17. Tunstall SM, Penning-Rowsell EC, Tapsell SM, Eden SE. River restoration: public attitudes and expectations. *Water Environ J*. 2000;14:363-370. doi:10.1111/j.1747-6593.2000.tb00274.x.
18. Webb AD, Falk DA, Finch DM. *Fire Ecology and Management in Lowland Riparian Ecosystems of the Southwestern United States and Northern Mexico*. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station; 2019:132. https://www.fs.fed.us/rm/pubs_series/rmrs/gtr/rmrs_gtr401.pdf.
19. Levick LR, Goodrich D, Hernandez M, et al. *The Ecological and Hydrological Significance of Ephemeral and Intermittent Streams in the Arid and Semi-arid American Southwest*. U.S. Environmental Protection Agency and USDA/ARS Southwest Watershed Research Center; 2008:116. https://www.epa.gov/sites/production/files/2015-03/documents/ephemeral_streams_report_final_508-kepner.pdf.
20. Palmer MA, Bernhardt Es, Allan JD, et al. Standards for ecologically successful river restoration. *J Appl Ecol*. 2005;42:208-217. doi:10.1111/j.1365-2664.2005.01004.x.
21. Branson FA, Gifford GF, Renard KB, Hadley RF. *Rangeland Hydrology*. Littleton, CO: Society for Range Management; 1981:1.
22. Gellis AC, Cheama A, Laahty V, Lalio S. Assessment of gully-control structures in the Rio Nutria Watershed, Zuni Reservation, New Mexico. *JAWRA J Am Water Resour Assoc*. 1995;31:633-646. doi:10.1111/j.1752-1688.1995.tb03390.x.
23. Neary DG, Ffolliott PF, DeBano LF. Hydrology, ecology, and management of riparian areas in the Madrean Archipelago. In: Gottfried GJ, Gebow BS, Eskew LG, Edminster CB, eds. *Connecting Mountain Islands and Desert Seas: Biodiversity and Management of the Madrean Archipelago II*. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station; 2005:316-319. http://www.fs.fed.us/rm/pubs/rmrs_p036/rmrs_p036_353_356.pdf.
24. Baker MB Jr, DeBano LF, Ffolliott PF. Hydrology and watershed management in the Madrean Archipelago. In: DeBano LH, Ffolliott PH, Ortega-Rubio A, Gottfried GJ, Hamre RH, Edminster CB, eds. *Biodiversity and Management of the Madrean Archipelago: The Sky Islands of Southwestern United States and Northwestern Mexico*. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1995:329-337.
25. Norman LM, Sankey JB, Dean DJ, et al. Quantifying geomorphic change at ephemeral stream restoration sites using a coupled-model approach. *Geomorphology*. 2017;283:1-16. doi:10.1016/j.geomorph.2017.01.017.
26. Geyik MP. Gully control. In: *Watershed Management Field Manual*. Food and Agricultural Organization of the United Nations; 1986. FAO Conservation Guide Series; vol 2. http://www.fao.org/docrep/006/ad082e/ad082e00.htm.
27. Zeedyk B, Clothier V. *Let the Water Do the Work: Induced Meandering, an Evolving Method for Restoring Incised Channels*. Santa Fe, NM: Quivira Coalition; 2009.
28. Food and Agriculture Organization of the United Nations. Road design and construction in sensitive watersheds. In: *Watershed Management Field Manual*. Conservation Guide No. 13. Food and Agricultural Organization of the United Nations; 1998. http://www.fao.org/3/T0099E/T0099E00.htm.
29. Heede BH. *Design, Construction and Cost of Rock Check Dams*. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1970.
30. Lancaster B. *Rainwater Harvesting for Drylands and Beyond*. 2nd ed., revised and expanded. Tucson, AZ: Rainsource Press; 2013.
31. Fish SK, Fish PR, Villalpando ME, eds. *Trincheras Sites in Time, Space, and Society*. Tucson: University of Arizona Press; 2007.
32. Di Peso CC. *Casas Grandes: A Fallen Trading Center of the Gran Chichimeca*. Vol. 2. Dragoon, AZ: Amerind Foundation, Inc; 1974.
33. Herold LC. *Trincheras and Physical Environment Along the Rio Gavilan, Chihuahua, Mexico*. Publications in Geography #65-1. Denver: Department of Geography, University of Denver; 1965.
34. Howard WA, Griffiths TM. *Trinchera Distribution in the Sierra Madre Occidental, Mexico*. Denver: Department of Geography, University of Colorado Denver; 1966:104.
35. Leopold A, Schwartz CW. *A Sand County Almanac: With Other Essays on Conservation from Round River*. Oxford, UK: Oxford University Press; 1966.
36. Woodbury RB. *Prehistoric Agriculture at Point of Pines, Arizona*. Washington, DC: Society for American Archaeology; 1961. https://www.jstor.org/stable/25146652.
37. Fish PR, Fish SK. “Tumamoc Hill Trincheras Site”—Site Tour. http://www.old-pueblo.org/event/tumamoc-hill-trincheras-site-site-tour/. Published 2016.
38. Anyon R, LeBlanc SA. *The Galaz Ruin: A Prehistoric Mimbres Village in Southwestern New Mexico*. Albuquerque: University of New Mexico Press; 1984.
39. Doolittle WE. The use of check dams for protecting downstream agricultural lands in the prehistoric southwest: a contextual analysis. *J Anthropol Res*. 1985;41:279-305. doi:10.2307/3630595.
40. Rosgen DL. A classification of natural rivers. *Catena*. 1994;22:169-199.
41. Rosgen D. *Applied River Morphology*. 2nd ed. Fort Collins, CO: Wildland Hydrology; 1996.
42. Lave R. Freedom and constraint: generative expectations in the US stream restoration field. *Geoforum*. 2014;52:236-244. doi:10.1016/j.geoforum.2013.03.005.
43. Juracek KE, Fitzpatrick FA. Limitations and implications of stream classification. *JAWRA J Am Water Resour Assoc*. 2003;39:659-670. doi:10.1111/j.1752-1688.2003.tb03683.x.
44. Simon A, Doyle M, Kondolf M, Shields F, Rhoads B, McPhillips M. Critical evaluation of how the Rosgen classification and associated “natural channel design” methods fail to integrate and quantify fluvial processes and channel response. *JAWRA J Am Water Resour Assoc*. 2007;43:1117-1131. doi:10.1111/j.1752-1688.2007.00091.x.
45. Rosgen D. *Applied River Morphology*. 2nd ed. Wildland Hydrology: Pagosa Springs, Colo; 1996. ISBN 978-0-9653289-0-6.
46. Rosgen DL. The application of stream classification using the fluvial geomorphology approach for natural channel design: the rest of the story. Paper presented at: World Environmental and Water Resource Congress 2006; May 21-25, 2006; Omaha, NE. doi:10.1061/40856(200)343.
47. Eekhout JPC, Hoitink AJF. Chute cutoff as a morphological response to stream reconstruction: the possible role of backwater: chute cutoff after stream restoration. *Water Resour Res*. 2015;51:3339-3352. doi:10.1002/2014WR016539.
48. Dobie K. An amateur rancher brings the wastelands of the Southwest back to life. *CNN*. September 21, 2012. http://www.cnn.com/2012/09/21/living/oprah-rancher/index.html. Accessed June 17, 2013.
49. Barry T. Transborder drylands restoration: vision and reality after three decades of innovative partnerships on the U.S.-Mexico border. *SAPIENS Surv Perspect Integrating Environ Soc*. 2014;7.2. http://sapiens.revues.org/1553. Accessed September 30, 2014.
50. Minckley WL. *Ecosystem Repair by Headwater Erosion Control: West Turkey Creek, Chiricahua Mountains, Arizona*. New York NY: Clark Foundation; 1998. http://www.nativefishlab.net/library/textpdf/15854.pdf. Accessed March 6, 2014.
51. Groundwater Awareness League. ADWR vs Austins. http://www.g-a-l.info/ADWRvsAustins.pdf. Accessed November 18, 2019.
52. Moore D, Green D. *Task # 10: Final Report, Prepared for: Water Protection Fund Grant 03-117WPF: Lynx Creek Restoration at Sediment Trap #2 Project*. Arizona: U.S. Forest Service, Arizona State University, and Arizona Water Protection Fund; 2006:50.
53. Norman LM, Pulliam HR, Girard MM, et al. Editorial: combining the science and practice of restoration ecology; case studies of a grassroots binational restoration collaborative in the Madrean Archipelago Ecoregion (2014-2019) [published online ahead of print 2020]. *Air Soil Water Res*.
54. Sky Island Restoration Cooperative (SIRC). Annual reports. https://www.skyislandalliance.org/wp-content/uploads/2016/04/SIRC-2015-Annual-Report_Final.pdf. Published 2014–16.
55. Bradshaw AD. Restoration: an acid-test for ecology. In: Jordan WR, Gilpin ME, Aber JD, eds. *Restoration Ecology*. Cambridge, UK: Cambridge University Press; 1987:22-29.
56. Heede BH. *A Study of Early Gully-Control Structures in the Colorado Front Range*. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1960:45: http://www.fs.fed.us/rm/pubs_exp_forests/manitou/rmrs_1960_heede_b001.pdf.
57. Peterson HV, Branson FA. Effects of land treatments on erosion and vegetation on rangelands in parts of Arizona and New Mexico. *J Range Manag*. 1962;15:220. doi:10.2307/3895254.
58. Hadley RF, Lusby GC. Runoff and hillslope erosion resulting from a high-intensity thunderstorm near Mack, Western Colorado. *Water Resour Res*. 1967;3:139-143.
59. DeBano LF, Heede BH. Enhancement of riparian ecosystems with channel structures. *JAWRA J Am Water Resour Assoc*. 1987;23:463-470.
60. Nichols MH, McReynolds K, Reed C. Short-term soil moisture response to low-tech erosion control structures in a semiarid rangeland. *CATENA*. 2012;98:104-109. doi:10.1016/j.catena.2012.06.010.
61. Polyakov VO, Nichols MH, McClaran MP, Nearing MA. Effect of check dams on runoff, sediment yield, and retention on small semiarid watersheds. *J Soil Water Conserv*. 2014;69:414-421. doi:10.2489/jswc.69.5.414.
62. Lucas-Borja ME, Zema DA, Hinojosa Guzman MD, et al. Exploring the influence of vegetation cover, sediment storage capacity and channel dimensions on stone check dam conditions and effectiveness in a large regulated river in México. *Ecol Eng*. 2018;122:39-47. doi:10.1016/j.ecoleng.2018.07.025.
63. Nichols MH, Polyakov VO, Nearing MA, Hernandez M. Semiarid watershed response to low-tech porous rock check dams. *Soil Sci*. 2016;181:275-282. doi:10.1097/SS.0000000000000160.
64. Nichols MH, Polyakov VO. The impacts of porous rock check dams on a semiarid alluvial fan. *Sci Total Environ*. 2019;664:576-582. doi:10.1016/j.scitotenv.2019.01.429.

65. Nichols MH, Magirl C, Sayre NF, Shaw JR. The geomorphic legacy of water and erosion control structures in a semiarid rangeland watershed: the geomorphic legacy of water and erosion control structures. *Earth Surf Process Landf.* 2018;43:909-918. doi:10.1002/esp.4287.
66. Young TP, Petersen DA, Clary JJ. The ecology of restoration: historical links, emerging issues and unexplored realms: ecology of restoration. *Ecol Lett.* 2005;8:662-673. doi:10.1111/j.1461-0248.2005.00764.x.
67. Norman LM, Villarreal ML, Pulliam HR, et al. Remote sensing analysis of riparian vegetation response to desert marsh restoration in the Mexican Highlands. *Ecol Eng.* 2014;70C:241-254. doi:10.1016/j.ecoleng.2014.05.012.
68. Goodrich DC, Burns IS, Unkrich CL, et al. KINEROS2/AGWA: model use, calibration, and validation. *Trans ASABE* 2012; 55:1561-1574. http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140009153.pdf.
69. Norman LM, Huth H, Levick L, et al. Flood hazard awareness and hydrologic modelling at Ambos Nogales, United States–Mexico border. *J Flood Risk Manag.* 2010;3:151-165. doi:10.1111/j.1753-318X.2010.01066.x.
70. Norman LM, Levick LR, Guertin DP, et al. *Nogales Flood Detention Study.* U.S. Geological Survey Open-File Report 2010-1262. 2010:112. https://pubs.usgs.gov/of/2010/1262/
71. Wilson NR, Norman LM. Analysis of vegetation recovery surrounding a restored wetland using the normalized difference infrared index (NDII) and normalized difference vegetation index (NDVI). *Int J Remote Sens.* 2018;39:3243-3274. doi:10.1080/01431161.2018.1437297.
72. Wilson NR, Norman LM. Vegetation response to landscape conservation in the sky islands. *Arizona Native Plant Society*, Plant Press. Winter 2019:27-31.
73. Wilson NR, Norman LM. Vegetation response to landscape conservation in the Sky Islands. *Arizona Native Plant Society*, The Plant Press. Winter 2019;42(2):27-31. https://aznps.com/the-plant-press/
74. Smith CF, Cordova JT, Wiele SM. *The Continuous Slope-Area Method for Computing Event Hydrographs.* U.S. Geological Survey; 2010. http://pubs.usgs.gov/sir/2010/5241/. Accessed December 2, 2013.
75. Norman LM, Brinkerhoff F, Gwilliam E, et al. Hydrologic response of streams restored with check dams in the Chiricahua Mountains, Arizona. *River Res Appl.* 2016;32:519–527. doi:10.1002/rra.2895.
76. Norman L, Callegary J, Lacher L, et al. Modeling riparian restoration impacts on the hydrologic cycle at the Babacomari Ranch, SE Arizona, USA. *Water.* 2019;11:381. doi:10.3390/w11020381.
77. Fandel CA. The effect of gabion construction on infiltration in ephemeral streams [Master of Science]. The University of Arizona; 2016. https://repository.arizona.edu/handle/10150/622852
78. iRIC Project. *Nays2DH Solvers Manual.* 60 p. Published 2016. https://i-ric.org/en/download/nays2d-solver-manual/. Accessed May 3, 2016. .
79. Arnold JG, Kiniry JR, Srinivasan R, Williams JR, Haney EB, Neitsch SL. *Soil and Water Assessment Tool Input/Output Documentation Version 2012.* College Station: Texas Water Resources Institute; 2012. https://swat.tamu.edu/media/69296/swat-io-documentation-2012.pdf.
80. Norman LM, Niraula R. Model analysis of check dam impacts on long-term sediment and water budgets in Southeast Arizona, USA. *Ecohydrol Hydrobiol.* 2016;16:125-137. doi:10.1016/j.ecohyd.2015.12.001.
81. Callegary JB, Norman LM, Eastoe CJ, Sankey JB, Youberg A. Preliminary assessment of carbon and nitrogen sequestration potential in fire-affected soils and sediments in forest ecosystems, southwest USA. *Air Soil Water Res Spec Collect "Case Stud Grassroots Binatl Restor Collab Madrean Archipel Ecoregion 2014-2019."* (Forthcoming) 2020.
82. Schneider L, La Hoz Theuer S. Environmental integrity of international carbon market mechanisms under the Paris Agreement. *Clim Policy.* 2019;19:386-400. doi:10.1080/14693062.2018.1521332.
83. SolVES. *Social Values for Ecosystem Services, Version 3.0 (SolVES 3.0)—Documentation and User Manual.* Washington, DC: U.S. Department of the Interior and U.S. Geological Survey; 2015. Open File Repor 2015-1008.
84. Petrakis RE, Norman LM, Lysaght O, et al. Mapping perceived social values to support a respondent-defined restoration economy: case study in Southeastern Arizona, USA. *Air, Soil and Water Research*; Special Collection, "Case Studies of a Grassroots Binational Restoration Collaborative in the Madrean Archipelago Ecoregion (2014-2019)." 2020. https://doi.org/10.1177%2F1178622120913318
85. Freimund CA, Garfin GM, Norman LM. Public values, flood risk perception, and resilience in ambos Nogales [Poster]. Presented at: Society of Ecological Restoration Southwest Conference; November 8, 2019; Tucson, AZ.
86. Petrakis RE, Vaughn K, Norman LM, Weaver C, Pulliam HR, Pritzlaff R. Using an experimental landscape to develop a regional ecosystem services approach to watershed restoration. Presented at: Madrean Conference 2018 Collaboration Now for the Future: Biodiversity and Management of the Madrean Archipelago IV; May 14, 2018; Tucson, AZ.
87. Norman LM, Haberstich M, Niraula R, Wilson NR, Middleton BR. *Development Implication on Hydrologic Ecosystem Services in the Aravaipa Canyon Watershed, SE Arizona.* Tucson, AZ: U.S. Geological Survey; 2018:51.
88. Tosline DJ, Norman LM, Greimann BP, et al. Hydrologic research pre- and post-low impact development in an ephemeral drainage. Presented at: U.S. Geological Survey Western Geographic Science Center Webinar; April 8, 2020; Phoenix, AZ.