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# Ecosystem Services of Riparian Restoration: A Review of Rock Detention Structures in the Madrean Archipelago Ecoregion

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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 Madreño. 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

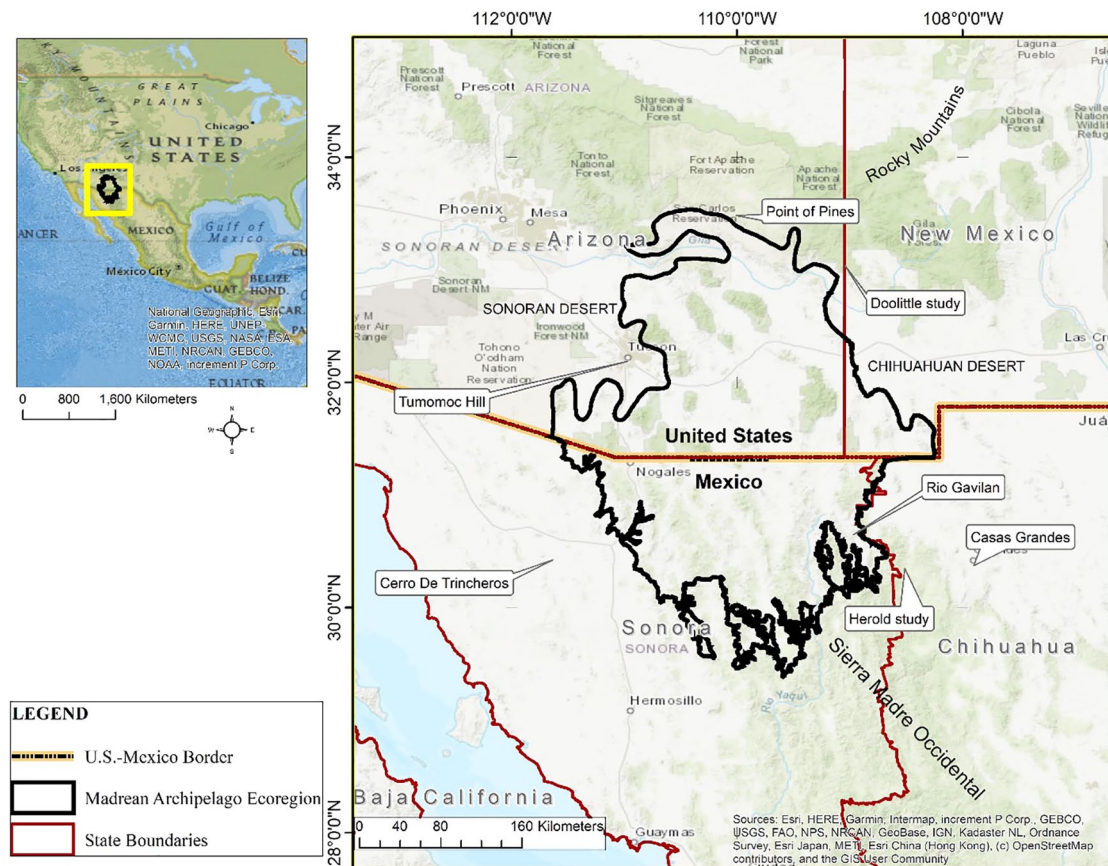
Human settlements and land-use practices have resulted in habitat degradation and the loss of biodiversity in the United States-Mexico borderlands.<sup>1</sup> These arid and semiarid landscapes have recently been subject to a multidecadal drought, with repercussions still looming related to climate.<sup>2,3</sup> And, as populations grow, resources become more imperiled and depleted.<sup>4–6</sup> Watershed restoration projects attempt to bring ecosystems back to natural conditions, although this can be challenging, given the dynamic nature of ecosystems.<sup>7</sup> 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.<sup>8</sup> Stakeholder and economic support is tied to the success of ecological restoration projects.<sup>6</sup> In return, restoration projects can provide measurable benefits to people, which is known as ecosystem services.<sup>7</sup> Predegradation conditions are largely unknown globally and hence, restoration practitioners are encouraged to overcompensate accommodations of both biodiversity and ecosystem services.<sup>9</sup> This idea has further evolved to include changes in

response to altered climate.<sup>10,11</sup> There is a demand for applied environmental science that can be used to form markets in restoration ecosystems services.<sup>12</sup>

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.<sup>13,14</sup> 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.<sup>15</sup> 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,<sup>16,17</sup> especially in aridlands. Ecological systems, such as desert riparian areas, are particularly threatened and are in need of conservation action.<sup>18</sup> These ephemeral and intermittent streams provide many direct and indirect landscape-hydrologic connections.<sup>19</sup> Previous researchers have indicated that river restoration assists the establishment of improved biophysical processes in degraded waterways and should be



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**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.<sup>16,20</sup> In this article, restoration of arid and semi-arid 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.<sup>16</sup> 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 evaluate 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.<sup>19,21</sup> Arroyo cutting and gullying are noted regionally to be increasing since the latter part of the 19th century.<sup>22</sup> Communities of riparian vegetation occupy floodplains adjacent to streams where the water table is near the surface most of the year.<sup>23</sup> The condition of these networks is dependent on movement and storage of sediments through the channel systems.<sup>23</sup> 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 <i>Trincheras</i>	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.<sup>37</sup>

and channel integrity.<sup>23</sup> Groundwater withdrawals can reduce surface flows and compromise dependent processes.<sup>24</sup> Overgrazing, fire suppression, and weather extremes (drought and high-intensity rain) have led to ecoregion-wide watershed degradation.<sup>24</sup> 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.<sup>24</sup>

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.<sup>25</sup> 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.<sup>26–30</sup> 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).<sup>31–36</sup> 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.<sup>36</sup>

Archeological evidence indicates that check dams were installed in southwestern New Mexican mountains to reduce high flows and sedimentation to a *ciénega*, or desert wetland, located downstream, that was likely cultivated in prehistoric times (CE 750–1150).<sup>38,39</sup> 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.<sup>39</sup> The Point of Pines area was occupied from 2000 BCE to CE 1450, with evidence of RDS built in 1000 (CE),<sup>36</sup> and *trincheras* dating back to 1100 to 1450 (CE) have been studied in northwestern Chihuahua, Mexico.<sup>33</sup> 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.<sup>33</sup> *Trincheras* found in the Sierra Madre Occidental Mountains irrigated the downstream floodplain by increasing runoff.<sup>32</sup> The cost of construction was considered low in terms of labor, especially compared to the benefits received.<sup>31,37,39</sup> 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)<sup>40,41</sup> 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;<sup>42</sup> however, some oppose the NCD approach for use in stream restoration, suggesting it may oversimplify complex fluvial processes and channel response.<sup>13,43,44</sup> It should be noted, however, that little data are available to resolve these contentions.<sup>13</sup> While careful responses to critics have been documented with information on the proper use and/or abuse of NCD methods for river restoration,<sup>45,46</sup> there continues to be a need for scientific analysis and data to improve restoration design and application.<sup>46</sup> 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.<sup>27</sup> 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.<sup>47</sup>

Beginning in the mid-1980s, check dams, gabions, and *trincheras* were installed in what is now ~800 km<sup>2</sup> of private landholdings on either side of the United States-Mexico border to enhance wildlife habitat.<sup>48,49</sup> 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.<sup>50</sup> However, use of these RDS was not without its critics. Induced-meander practitioners condemned the use of check dams as being expensive and ineffective,<sup>41</sup> suggesting they do not restore natural rivers and will ultimately fail.<sup>27</sup> 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.<sup>51</sup> 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.<sup>52</sup>

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.<sup>53,54</sup> 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.<sup>20,55</sup> 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*

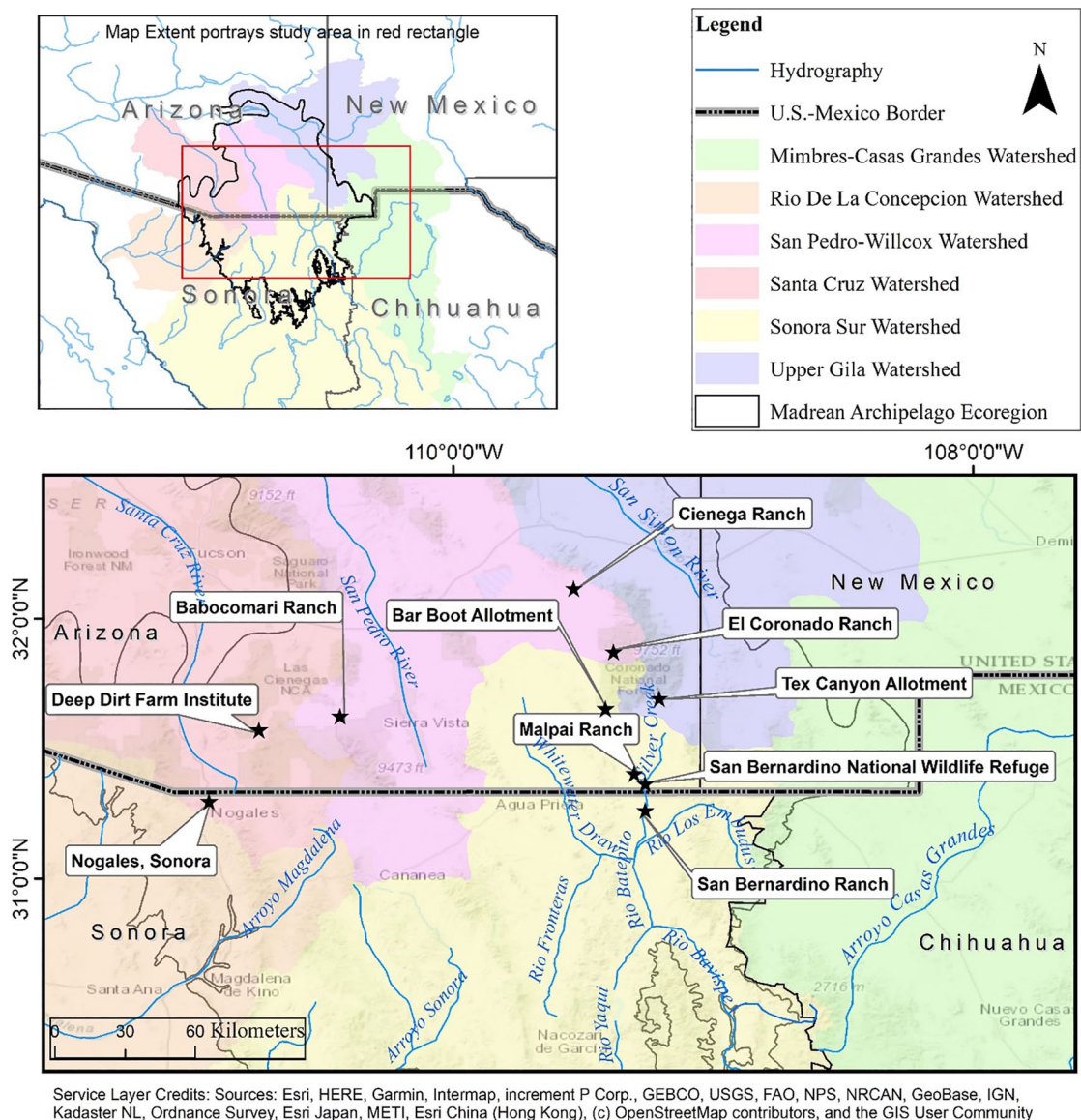
Researchers at the US Forest Service (USFS) used gully-control structures (check dams) in the Colorado Front Range in the 1960s, documenting benefits of erosion control and water quality improvements both on-site and downstream.<sup>56</sup> Other USFS studies describe earthen dams and dike spreaders, 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.<sup>57</sup> Low dams and barriers have been documented by the USFS to impact sedimentation depending on particle-size distribution and availability of material.<sup>58</sup> While positive impacts of these RDS on streamflow hydraulics, sedimentation, and riparian zone establishment were documented, they could also be destructive.<sup>59</sup> As a result, scientists suggested that the complexity of riparian ecosystems requires a multidisciplinary approach to evaluate impacts of channel structures.<sup>59</sup>

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.<sup>60-63</sup> 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.<sup>60</sup> Although researchers documented an initial postconstruction decrease in runoff from small rainstorms,<sup>61,63</sup> this response was not persistent.<sup>64</sup> 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.<sup>65</sup>

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%).<sup>22</sup> 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



**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.<sup>6,18,66</sup> The Aridland Water Harvesting Study comprises multiple investigations examining potential ecosystem services of RDS, including large gabions (Figure 4),<sup>28</sup> 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.<sup>26-29</sup>

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.<sup>68</sup> Results portrayed flood-prone areas that might be appropriate for management intervention.<sup>69</sup> 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])<sup>67</sup>; (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).<sup>69</sup> 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.<sup>70</sup>

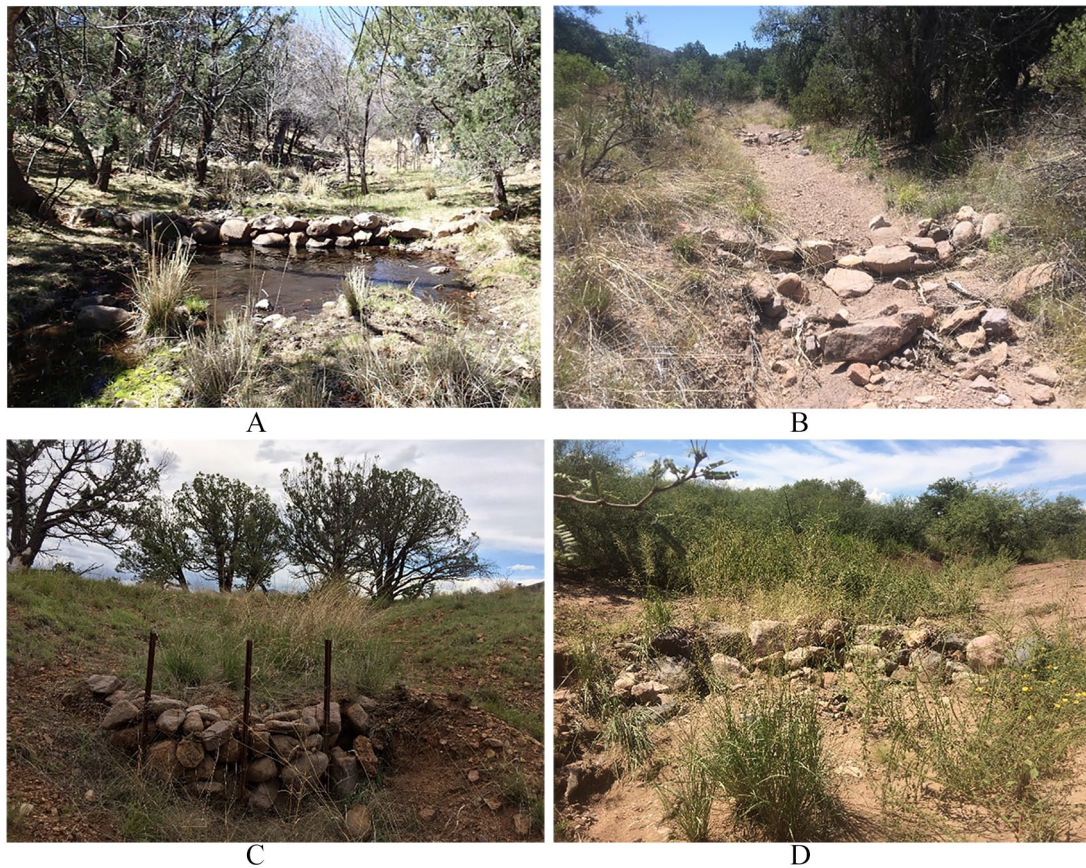
### *Habitat provisioning*

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)

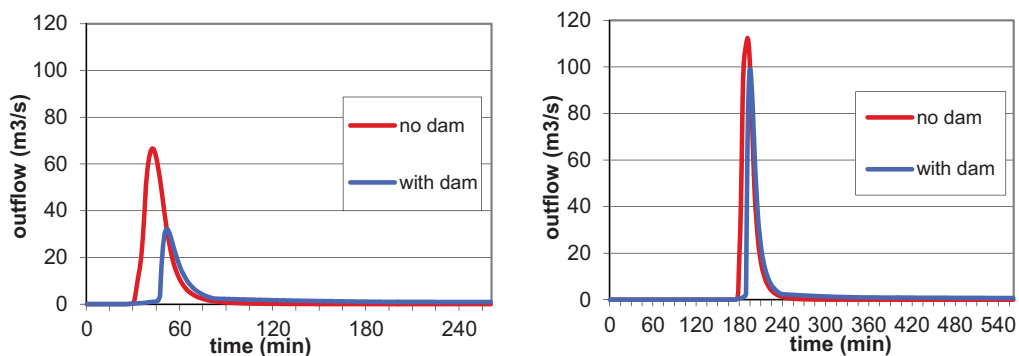
and by the Cuenca los Ojos (CLO) Foundation over the course of 20+ years to restore surface water for native fishes (Figures 3 and 4(B)). *Cienegas*, or desert wetlands, are biodiverse yet sensitive habitats imperiled by demands for water and by changing climates.<sup>18</sup> A remote-sensing analysis, 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*.<sup>67</sup>

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.



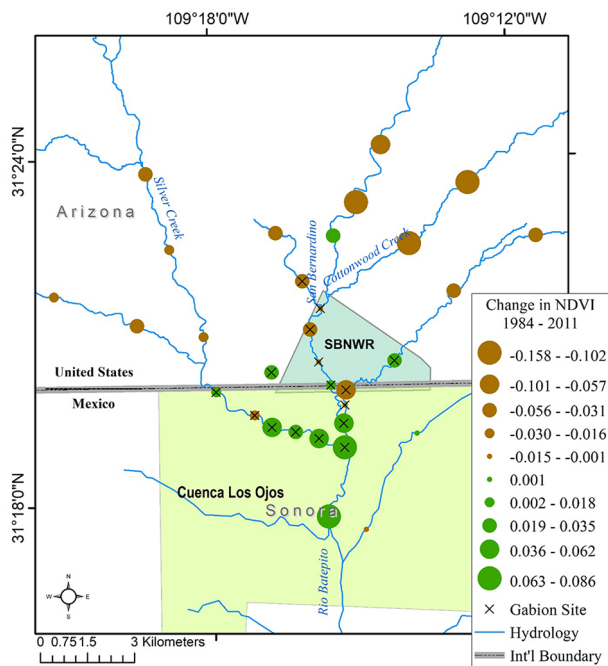
**Figure 6.** Gabion installation at the Cuesta Blanca subwatershed of Nogales, Sonora, Mexico, hydrograph results of modeling runoff response after a 10 year, 1-h storm event (left) and a larger 100 year, 6-h event (right).<sup>70</sup>

tributary and upland areas (Figure 8).<sup>71</sup> 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.<sup>71</sup>

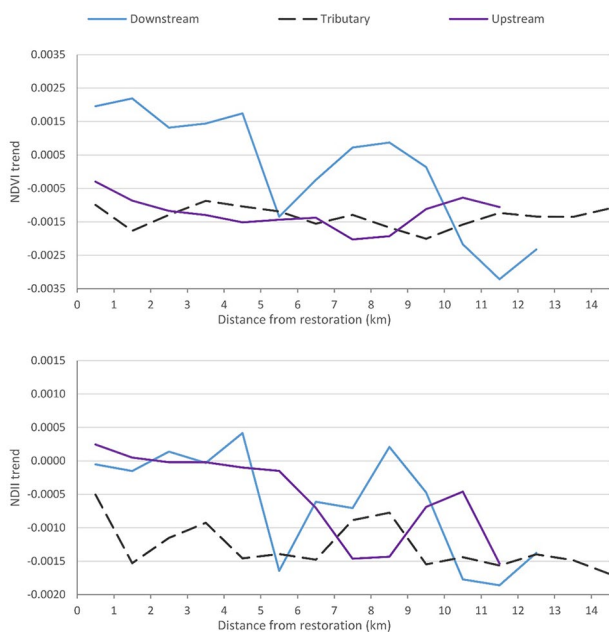
A field study was launched in 2014 to monitor locations annually, during summer rainy seasons, to document on-the-ground measurements of vegetation abundance and species composition and changes that may not be observable using satellite imagery.<sup>72</sup> In the Chiricahua Mountains, the Sky Island 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)).<sup>53</sup> 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.<sup>72,73</sup>





**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).<sup>67</sup>



**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.<sup>71</sup>

### 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.<sup>74,75</sup> 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.<sup>75</sup> 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.<sup>76</sup> 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.<sup>77</sup> 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).<sup>76</sup> Model results indicated a potential increase in lateral soil water incurred from gabion installation, as previously hypothesized at the El Coronado Ranch study.<sup>75,76</sup>

### 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.<sup>78</sup> 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 versus untreated in paired-watershed study.<sup>75</sup>

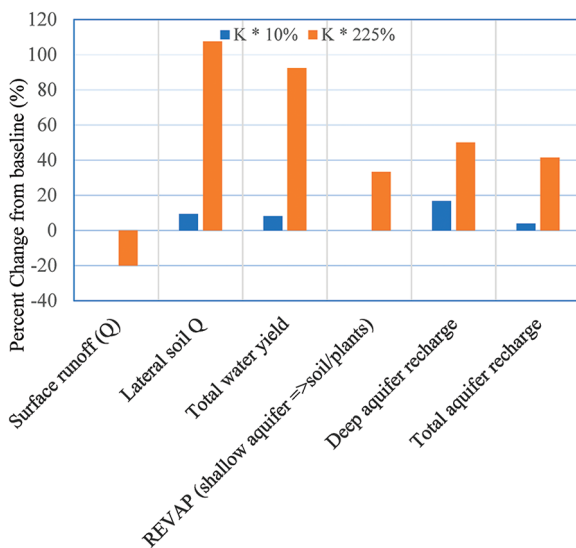


Figure 10. Chart portraying change predictions for the water budget in the future (2050) if gabions are installed throughout the watershed, where K = hydraulic conductivity.<sup>76</sup>

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

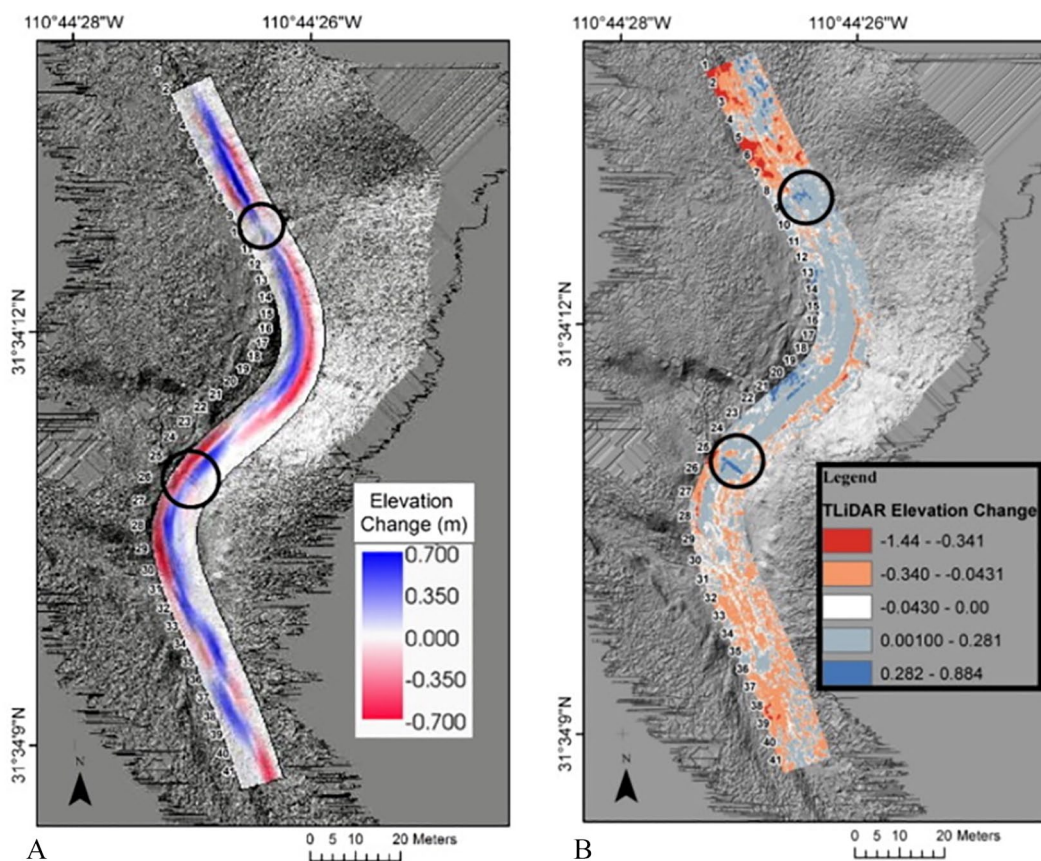
model data acquisitions and uncalibrated simulations, demonstrated the potential to use models to predict hydraulics and approximate associated trends and patterns of aggradation and degradation resulting from gabions before they are installed.<sup>25</sup>

The effect of check dam infrastructure on soil conservation was also evaluated using the Soil and Water Assessment Tool (SWAT)<sup>79</sup> at the El Coronado Ranch. The SWAT model was calibrated for streamflow using the discharge documented during the summer of 2013<sup>75</sup> 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.<sup>80</sup> 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.<sup>25</sup>

#### 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).<sup>25</sup>

Ranch. Results indicate the potential of check dams to increase carbon sequestration, especially in burned watersheds.<sup>81</sup> 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.<sup>81</sup> 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.<sup>82</sup>

### 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)<sup>83</sup> 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.<sup>84</sup> 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.<sup>85</sup>

### 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.<sup>13,43,86</sup> 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.<sup>53</sup>

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.<sup>69,70</sup> 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.<sup>67,71,75</sup> Rock detection structures can promote vegetation maintenance and health through drought, indicating increased water availability with positive effects extending up to 5 km downstream.<sup>67,71,72</sup> In some locations, 30-year-old structures are still functional for water and soil retention,<sup>25,80</sup> as well as carbon storage.<sup>81</sup> Social surveys indicate that people value the stream networks in their watershed and advocate for restoration.<sup>84</sup> Finally, studies have demonstrated that watershed models can be used for predictive-framework and decision-support.<sup>25,69,70,76,80,87</sup> These advances in restoration science, with science-based evidence that dispels prior assumptions, are being acknowledged by partner agencies who can revise management strategies<sup>53,88</sup> 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 valued, 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

Supplemental material for this article is available online.

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