Collaboration for Environmental Evidence **Library**

CEE review 10-002

HAVE ARID LAND SPRINGS RESTORATION PROJECTS BEEN EFFECTIVE IN RESTORING HYDROLOGY, GEOMORPHOLOGY, AND INVERTEBRATE AND PLANT SPECIES COMPOSITION COMPARABLE TO NATURAL SPRINGS WITH MINIMAL ANTHROPOGENIC DISTURBANCE?

Systematic Review

STACEY, C.J. (NÉE DAVIS)[1], SPRINGER, A. E.[1] & STEVENS, L.E.[2]

[1] School of Earth Sciences and Environmental Sustainability, Northern Arizona University, P.O. Box 4099, Flagstaff, AZ 86011, USA
[2]. Museum of Northern Arizona, 3101 North Fort Valley Road, Flagstaff, AZ 86001-8348, USA

Correspondence: cjd48@nau.edu
Telephone: 00+1+928-523-9403
Fax: 00+1+928-523-9220

Source of support: Northern Arizona University's Ecological Restoration Institute

Draft protocol published on website: 15 January 2010- Final protocol published on website:13 July 2010
Draft review published on website: 11 April 2011- Final review published on website:19 October 2011

Cite as: Stacey, C.J., Springer, A.E. & Stevens, L.E. 2011. Have arid land springs restoration projects been effective in restoring hydrology, geomorphology, and invertebrate and plant species composition comparable to natural springs with minimal anthropogenic disturbance? CEE review 10-002 (SR87). Collaboration for Environmental Evidence: www.environmentalevidence.org/SR87.html.

Summary

1. Background

Springs are places where groundwater is exposed at the earth's surface, often flowing naturally from bedrock or soil onto the land surface or into a body of surface water. There may be 10^5-10^6 springs in the United States, occupying a total area of 500-1000 km^2 (less than 0.001 % of the nation's land area). Springs, particularly those in arid regions, are vastly more complex, diverse, and productive than are adjacent uplands. At a national and continental scale, springs are among our most threatened ecosystems; in the American West, more than 90 % of springs are estimated to be ecologically impaired (Stevens and Meretsky, 2008). Springs are important ecologically because they provide habitats for a diverse array of aquatic and wetland plant and animal species, many of which are endangered or endemic (Anderson et al., 2003; Springer and Stevens, 2009). Odum's (1957) study of Silver Springs in Florida, which laid the groundwork for much of the science of ecosystem ecology, remains one of the few comprehensive examples of springs ecosystem function. In addition, springs are culturally critical landscapes, the focus of profound traditional, religious and ethnoecological attention by indigenous cultures throughout the world (Stevens and Meretsky, 2008).

While some restoration efforts have taken place in arid land springs ecosystems, few have been sufficiently well monitored to evaluate their success. Knowledge of the location, quantity, and quality of a resource is an important first step towards effective conservation and restoration (Thompson et al., 2002). However, the distribution, ecological condition, and threats facing many springs ecosystems are poorly known, and therefore potential restoration needs have heretofore remained unidentified, a gap this document begins to fill. In addition, development and adherence to a springs inventory and monitoring protocol has not been adopted, in part because of the many different jurisdictions under which researchers and land managers operate and a lack of cross-jurisdictional coordination. As more information about springs ecosystems becomes available, there may be compelling evidence to improve stewardship, restoration, and monitoring of these ecosystems. This review examines the state of knowledge of arid land springs ecosystem restoration and monitoring to help springs ecosystem stewards better plan and prioritize management and restoration actions.

2. Objectives

The objectives of this review are to 1) summarize the state of knowledge about arid land springs restoration, and 2) determine whether springs ecosystem restoration projects in arid regions have been effective in restoring hydrology, geomorphology, and biological assemblage composition and structure in relation to those at natural springs with minimal anthropogenic disturbances

3. Methods

A list of search criteria was created to include specific search terms, as well as inclusion and exclusion criteria to help in eliminating irrelevant studies. After relevant literature was found and reviewed, information on study characteristics, methods, and results were summarized in a master spreadsheet. These studies were then analyzed for quality determined from Pullin and Knight's (2003) hierarchy of evidence and filtered based on the quality rating. Data from studies considered to be sufficiently robust to meet data quality standards were analyzed as to restoration criteria and success using the Society for Ecological Restoration (SER) International Science & Policy Working Group (2004) criteria for successful restoration.

4. Main results

Search results and elimination processes returned 15 studies analyzed for this review. The great inconsistency in the rationale for and in the implementation, monitoring, and reporting of springs restoration efforts precluded a meta-statistical analyses of the results. Individual studies were reviewed and results were summarized and analyzed for quality. Restoration success was difficult to assess in most projects because of limited monitoring and follow-up reporting. When restoration success was judged by whether identified restoration objectives were accomplished, most of the studies were rated as successful.

5. Conclusions

Standardized ecosystem condition and restoration assessment protocols are needed to more clearly understand the success of springs restoration projects, and could be developed through the collaboration of springs restoration stewards. Such a contribution would be highly beneficial to from a conservation perspective and to land resource managers and restoration practitioners. Improved understanding to how specific attributes or characteristics of springs ecosystems respond to specific restoration activities provided in this review will help managers develop rationales, estimate costs, prioritize projects, select appropriate treatments, improve monitoring, and incorporate feedback into future management and restoration activities.

1. Background

1.1 Introduction

Springs are places where groundwater is exposed at the earth's surface, often flowing naturally from bedrock or soil onto the land surface or into a body of surface water. A comparison of the density of named springs in the United States (Stevens and Meretsky, 2008) with several intensive surveys of springs in Texas (Brune, 1981), Wisconsin (Macholl, 2007), Arizona (Ledbetter et al., 2010), and other states indicates that fewer than 10 percent of springs have been named or mapped. Therefore, we estimate that 10^5-10^6 springs may exist in the United States. Our observations and surveys of springs in the south-western United States, Alberta, Pennsylvania, and Florida indicate that the habitat area of most springs is relatively small (0.01-0.1 ha), and therefore springs likely occupy a total area of only 500-1000 km^2 (less than 0.001 % of the nation's land area). Springs, particularly those in arid regions, are vastly more complex, diverse, and productive than are adjacent uplands (Grand Canyon Wildlands Council, 2003; Perla and Stevens, 2008), and provide essential ecological goods and services to surrounding landscapes and cultures. Unfortunately, springs have been widely exploited by humans for domestic and livestock water supplies and habitat. Estimates of the number of springs sustaining ecological impairment in the American West exceed 90 % (Stevens and Meretsky, 2008), and at national and global scales, springs are among the most threatened ecosystems (Hendrickson and Minckley, 1984; Kresic and Stevanovic, 2010; Cantonati et al., 2011).

Although Odum's (1957) studies of Silver Springs in Florida laid the groundwork for much of the science of ecosystem ecology, his study remains one of only a few comprehensive efforts to describe springs ecosystem structure, pattern of energy flow, and trophic interactions. Among the only other comprehensive descriptions of a springs ecosystem are those of Blinn (2008) and his colleagues at Montezuma Well (a large limnocrene (

Table 1) in central Arizona) and the ecology of hot springs in Yellowstone National Park, Wyoming (e.g., Brock, 1994). Limnocrene and hot springs are only two of at least a dozen different types of springs (

Table 1; Springer et al., 2008), and while detailed description of hanging gardens springs has been undertaken (e.g., Welsh, 1989), little systematic ecosystem science attention has been paid to the other types of springs. Springs are important because they are provide habitat for a diverse array of aquatic and wetland plant and animal species, many which are rare, endangered, or endemic (Anderson et al., 2003; Springer and Stevens, 2009).

While some arid land springs ecosystem restoration efforts have taken place, there has been little synthesis of monitoring or other project information through which to assess restoration success. Basic information on springs ecosystem ecology and evaluation of restoration potential remains unidentified. In addition, the development and use of comprehensive springs inventory and monitoring protocols has only recently begun, in part because of the many different springs types, the cross-disciplinary nature of springs research, and the multiple, uncoordinated administrative contexts under which researchers and land managers operate. Limited scientific study and conservation attention has limited the knowledge available to develop and implement appropriate springs restoration theory and restoration protocols. Knowledge of the location, quantity, and quality of a resource is the first step in effective conservation and restoration, and such information is generally lacking (Thompson et al., 2002). More in-depth information about springs ecosystems status will likely promote greater efforts to protect, restore, and monitor these ecosystems.

This review contributes to the state of knowledge of arid land springs ecosystems restoration, and improves the relevance and consistency of monitoring approaches for springs ecosystems. Such efforts are needed to improve springs ecosystem stewardship, and that of all natural water resources in arid regions. This review also will benefit the future improvement and efficiency of springs restoration and monitoring projects by summarizing and reviewing the state of knowledge and methods used in past restoration and monitoring efforts.

1.2 Distribution of Springs

The distribution of springs at a global scale is difficult to determine due to the lack of mapping and inventory data. Many springs have not been documented, and therefore are not found in any databases. Many databases do not differentiate between springs and small bodies of water, such as tanks, ponds, or even wells. Also, it seems likely that many springs remain to be officially mapped, particularly those in topographically diverse landscapes. Thus, it is difficult to draw clear conclusions about the distribution of springs; however, springs occur in much greater density than has previously been recognized. In the United States, there is an abundance of springs in the Rocky Mountain and Intermountain West states: the density of named springs density in Oregon and Arizona exceeds 0.016 springs/km^2, while springs density in Kansas and other Great Plains states is less than 0.002 springs/km^2 (Stevens and Meretsky, 2008).

1.2.1 Springs definition

Springs are found in a wide array of unique geological and geomorphic settings. Springer and Stevens (2009) describe 12 spheres of discharge, or 12 different forms of groundwater emergence at the Earth's surface, including: 1) springs that emerge in caves, 2) exposure springs, 3) artesian fountains, 4) geysers, 5) gushets, 6) contact hanging gardens, 7) helocrene wet meadows, 8) hillslope springs, 9) hypocrene buried springs, 10) limnocrene surficial lentic pools, 11) mound forms, and 12) rheocrene lotic channel floors (

Table **1**).

Table 1. Descriptions of springs sphere of discharge, or emergence environments (Modified from Springer and Stevens, 2009).

Sphere of Discharge	Emergence setting and hydrogeology	Example	Reference
Cave	Emergence in a cave in mature to extreme karst with sufficiently large conduits	Kartchner Caverns, AZ	Springer et al. (2008)
Exposure springs	Cave, rock shelter fractures, or sinkholes where unconfined aquifer is exposed near the land surface	Devils Hole, Ash Meadows, NV	Springer et al. (2008)
Fountain	Artesian fountain with pressurized CO_2 in a confined aquifer	Crystal Geyer, UT	Springer et al. (2008)
Geyser	Explosive flow of hot water from confined aquifer	Riverside Geyser, WY	Springer et al. (2008)
Gushet	Discrete source flow gushes from a cliff wall of a perched, unconfined aquifer	Thunder River, Grand Canyon, AZ	Springer et al. (2008)
Hanging garden	Dripping flow emerges usually horizontally along a geologic contact along a cliff wall of a perched, unconfined aquifer	Poison Ivy Spring, Arches, NP, UT	Springer and Stevens 2009
Helocrene (marsh) or cienega (wet meadow)	Emerges from low gradient wetlands; often indistinct or multiple sources seeping from shallow, unconfined aquifers	Soap Holes, Elk Island, NP, AB, Canada	Modified from Meinzer 1923; Hynes 1970; Grand Canyon Wildlands Council (2002)
Hillslope spring	Emerges from a hillslope (15-60^{o} slope); often indistinct or multiple sources	Ram Creek Hot Springs, BC, Canada	Springer et al. (2008)
Hypocrene	A buried spring where flow does not reach the surface, typically because of low discharge or high evaporation or transpiration	Mile 70L Springs, Grand Canyon, AZ	Springer et al. (2008)
Limnocrene - emerges from lentic pool(s)	Emergence of confined or unconfined aquifers in pool(s)	Grassi Lakes, AB, Canada	Modified from Meinzer 1923, Hynes 1970
(Carbonate) Mound-form	Emerges from a mineralized mound	Montezuma Well, AZ; Dalhousie Springs, Australia	Springer and Stevens 2009
Rheocrene - lotic channel floor	Flowing spring, emerges directly into one or more stream channels	Pheasant Branch, WI, US	Modified from Meinzer 1923, Hynes 1970

1.3 Ecological Roles of Springs Ecosystems

Springs provide numerous ecological resources and services, not only to humans, but also to other species and adjacent ecosystems (Perla and Stevens, 2008). Although individual springs are generally small in spatial area and sometimes rare at landscape scale, they are highly sensitive to anthropogenic activities. Landscape and regional water resource assessments and large-scale forest management planning have sparked interest in springs restoration, especially in arid regions because of their resource values, the extent of threats, and the very evident impacts. It is important to gain a more complete understanding of their ecological condition and threat profiles within groundwater basins to develop a sound understanding of baseline conditions before restoration activities proceed.

The ecology of springs ecosystems is poorly understood due to limited research; however, springs research has expanded in recent decades. The growing awareness of climate change has not yet extended to understanding the impacts on springs. Springs ecosystem ecology presently is a combination of many other disciplines including historical and structural geology, microclimatology, cave biology, lentic and lotic limnology, water law, and conservation science (Stevens and Meretsky, 2008).

Many species use or rely on springs as critical sources of water, forage, and habitat, and springs commonly support rare and endemic species. Some endemic species are entirely dependent on one or a few springs [e.g., MacDougall's flaveria (Asteraceae: *Flaveria macdougallii*), Ash Meadows Amargosa Pupfish (Cyprinodontidae: *Cyprinodon nevadensis mionectes*) and the Banff Springs Snail (Physidae: *Physella johnsoni*). Loss or severe dysfunction of the spring spells doom for such springs-obligate taxa.

1.4 Cultural Importance

Springs are considered as sacred places for many cultures. Humans have relied on springs for water, habitation, and hunting locations throughout our evolutionary existence (Stevens and Meretsky, 2008). Native Americans from western North America (e.g., Klamath Indians of southern Oregon, Nez Perce Indians of Rocky Mountains south of Missoula, Montana) believed hot springs had healing powers and were a place where the "Great Spirit" lived (Lund, 1995). Hot springs were also considered neutral ground, where warriors could travel to and rest without attack by other tribes (Lund, 1995). In North America and Australia, springs are of great cultural importance to indigenous peoples, and were essential to European exploration of arid regions during the early periods of colonization (Ponder, 2002). The cultural importance of springs is further indicated by the extent of their use and alteration (see section 1.5). Springs are widely used for bathing, water sources, rare mineral extraction, and in the case of geothermal springs, for heating (Stevens and Meretsky, 2008). Countries such as Iceland, Chile, New Zealand, and Japan are renowned for their hot springs, which are natural resources for tourism (Lin et al., 2010). Springs restoration planning and implementation efforts must take socio-cultural and economic compliance and issues into consideration.

1.5 Alterations of Springs Ecosystems

Human alteration of springs has occurred for millennia. Springs have been prominent sources of high quality water, and often have been used as a foundation resource for human settlement. Prominent anthropogenic threats to springs include groundwater withdrawal, geomorphic alteration of springs sources, diversion and capture of springs outflow, and modification of springs for livestock watering, and recreation, including swimming pools or thermal baths. Humans also have altered the natural disturbance regime at springs, through geomorphic alteration, focused livestock use, construction of spring boxes, and climate change. Innumerable springs and their associated biota throughout the world are imperilled by groundwater drawdown and other human impacts (Unmack and Minckley, 2008). Overgrazing, deforestation, urbanization, and other land and water uses have reduced springs ecosystem integrity directly, and indirectly by reducing watershed infiltration capacity and aquifer recharge, ultimately influencing the sustainability of aquifers that feed springs (Pringle and Triska, 2000; Stevens and Meretsky, 2008).

Human exploitation of springs, which began with hand-dug irrigation ditches, wells, and windmills, became prominent in the western United States during European colonization (Unmack and Minckley, 2008). Groundwater extraction rates commonly exceed recharge rates, and become unsustainable with agricultural practices (Pringle and Triska, 2000), and continue to expand with urbanization from population growth. Examples include Australian spring sites in the Great Artesian Basin that dried or nearly dried soon after water extraction began (Habermehl, 1983; Ponder, 2002), and springs in the Owens Valley of California that were dewatered by excessive groundwater pumping (Otis Bay Inc. and Stevens Ecological Consulting LLC, 2005).

Changes in flow volume or patterns of a spring or spring system can have a 'domino effect,' involving numerous, diverse, and intertwined biotic and physicochemical shifts (Unmack and Minckley, 2008). The three major factors determining the severity of impact of reduction in flow or spring diversion are shown in
TABLE **2**.

Table 2. Factors that determine the severity of reduced water flow.

	Major factors determining the severity of impact of reduction in flow or spring diversion (Unmack and Minckley, 2008):
1	Proportion of flow lost.
2	Reduction in downstream extent of the system as a result of less water or distance between nearby spring outflows
3	New connections made by diversions between nearby spring outflows

In addition, reduction of flow and concomitant slowing of the rate of water movement through the runout channel may increase water temperature during the warm season, ion concentration through evaporation, pH through increased interaction with benthic or macrophytic vegetation, and chemical precipitation rates. Such changes may take place abruptly if the water table is suddenly lowered, with increasing seasonal extremes as aquatic and riparian vegetation cover responds, or over longer time frames as regional climate changes.

1.6 Restoration of Springs Ecosystems

Many different types of restoration methods are utilized at springs ecosystems, including, but not limited to: 1) rehabilitation of springs orifice; 2) restoration to discharge channel and floodplain morphology; 3) removal of non-native species; 4) revegetation and reintroduction of native species; and, 5) reintroduction of periodic fires by prescribed burning. The type of restorative action is strongly dependant on the particular interests of the restoration management. Restoration projects may be focused on one particular aspect of the springs ecosystem (partial restoration), or are interested in restoring the full ecosystem (full restoration).

1.6.1 Rehabilitation and Protection of Springs Orifice and Discharge

Rehabilitation of springs sources may be completed by: 1) removal of diversion and capture structures (Muehlbauer et al., 2008); 2) reduction of groundwater pumping (Katz, 2010); 3) large ungulate exclusion from the springs source by fence installation (Anderson et al., 2003; AWPF, 2001; Brunson et al., 2001, GCWC, 2010, Long et al., 2004, Natural Channel Design, Inc., 2008); and 4) removal of overgrown vegetation (Kodric-Brown and Kodric, 2007). Restrictions of recreational activities (e.g., off-road vehicle use, camping) have also been utilized to protect springs and their watersheds (e.g., Brunson et al., 2001; Fossil Springs, Arizona). Flow reintroduction by removal of diversion and capture structures (i.e., berms, roads, etc.; Springer et al., 1999, GCWC, 2010, Natural Channel Design Inc., 2008), or by reducing surrounding groundwater pumping rates (Katz, 2010) can help improve the overall ecosystem health (Kresic and Stevanovic, 2010).

1.6.2 Geomorphological Restoration

Geomorphic restoration methods are frequently used in springs ecosystem rehabilitation. Channel stabilization structures are sometimes constructed to reduce erosion, slow flow rate, increase water level, reduce headcutting, and recreate the natural grade features (Long et al., 2004). Discharge channel stabilization structures include: log structures, riffle formations, and check dams. Examples of significant earth moving exist (e.g. Hoxworth Springs and Pakoon Springs, Arizona) in which large equipment was use to reform geomorphology and reconstruct channel geometry by creating appropriate meanders patterns and to re-attach channels to abandoned floodplains (Springer et al., 1999; Grand Canyon Wildlands Council, 2010). Along with these methods, revegetation techniques are also usually incorporated (Section 1.6.4). Negative impact of earth moving can be avoided or reduced by re-seeding with native grass, planting vegetation plugs, pole planting native phreatophytes, and covering bare soil with netting, straw, or wire fencing. These methods help reduce erosion of disturbed areas and increase site stability.

1.6.3 Non-native Species Control and Elimination

Non-native species control and elimination include vegetation, invertebrate, and vertebrate populations. Non-native species can be manually removed from the site, or less frequently, eliminated with herbicide or pesticide (Arizona Water Protection Fund, 2001; Weissenfluh, 2007). The use of herbicides and pesticides is not common because damage to native and desired species may occur. Installation of ungulate-proof fencing (Natural Channel Design, Inc., 2008) helps exclude livestock and undesirable grazing from elk or deer. Bullfrog (*Rana catesbiana*) fences also have been used to restrict bullfrog movement among springs (Grand Canyon Wildlands Council, Inc., 2010). If fencing is constructed, continued maintenance is usually required.

1.6.4 Revegetation

Revegetation and reintroduction of native plant species occurs through seeding and planting transplants. Recolonization may occur naturally if native species still occur in the area (e.g., at Pakoon Springs; Grand Canyon Wildlands Council, Inc., 2010). Irrigation systems may sometimes be necessary to help transplanted vegetation survive initial planting (AWPF, 2001). Transplanted stock is often best selected from areas near the springs ecosystem to ensure adaptation to the local environment.

1.6.6 Fire Reintroduction

Fire has been a common ecological disturbance in some springs ecosystems (e.g., Weisberg et al., 2010). Few springs restoration projects have yet utilized prescribed burning as a rehabilitation technique for springs ecosystems (e.g. Brunson et al., 2001). The goal of this restoration method is to reintroduce a more natural fire regime to upland watershed areas. Restoration projects that incorporated prescribed burning have reported positive effects (Brunson et al., 2001; Natural Channel Design, 2008). Prescribed burning can be used to control non-native vegetation or overgrown vegetation: the Muleshoe Ranch restoration project used prescribed fire to reduce shrub cover in the upland by 50 % (Brunson et al., 2003). Restoration treatments at Hart Prairie, Arizona also included using prescribed burning to thin ponderosa pine trees that were encroaching on the wet meadow area (Natural Channel Design, 2008).

2. Objectives

The objectives of this review were to examine springs ecosystem restoration in arid regions and to summarize restoration efforts and effectiveness. With this review, we hope to identify and resolve deficiencies in the state of springs restoration and monitoring knowledge in arid regions, and thus advance springs restoration ecology. Without such an undertaking, the challenges faced by those approaching springs restoration will continue to be addressed on a case-by-case basis. Continued repetition of mistakes and failure to communicate the lessons learned from restoration efforts may retard the momentum of springs conservation and regional water resources management. The qualitative review undertaken here will help clarify the scope of existing restoration activities, identify useful monitoring strategies, and improve the likelihood of success of strategies and projects. This review also provides information to help managers prioritize management or restoration actions, a necessary practice where financial resources are limited. While we provide qualitative review here, the great diversity of springs types, levels of human impact, and different approaches to environmental problem-solving makes restoration planning and implementation highly site-specific. Flexibility, creativity, and careful monitoring are needed to ensure the success of springs restoration projects, and systematic quantitative advice on springs restoration practices will require more data on projects, methods, and the resolution of major challenges.

2.1 Primary question

Have springs restoration projects in arid lands been effective in restoring springs ecosystem hydrology, geomorphology, and plant and invertebrate species composition comparable to conditions of natural springs with minimal anthropogenic disturbances?

3. Methods

3.1 Question formulation

We hypothesized that a critical mass of existing publications on springs restoration existed to undertake this analysis. We used collaborations with Northern Arizona University, the Museum of Northern Arizona, the University of Lethbridge, the Ecological Restoration Institute, and other research institutions and scientists as the source of information for this report.

3.2 Search strategy

Our goal was to identify springs restoration projects worldwide. Searches took place between December 2009 and January 2010, and in August 2010 (Appendix B). We searched the following electronic databases for studies using our search terms, and recorded the number of titles returned per database, and number of titles that were returned as duplicates (Appendix B).

Our search included all combinations of the following keywords:

- Springs (used interchangeably with natural springs, riparian springs, arid land springs, watersheds, and catchments); and,
- Restoration, prescribed burns (interchangeably with natural fire or wildfire), management, hydrology (interchangeably with hydrogeology), geomorphology (interchangeably with stabilization), conservation, fencing (interchangeably with enclosure), diversion.

Electronic databases available through Northern Arizona University's Cline Library were a primary source, and included:

- Academic Search Premier
- Environmental Science and Pollution Management
- Forest Science Database (Ovid)
- JSTOR
- ProQuest: Dissertations and Theses Full Text
- Science Direct
- Wilson OmniFile
- GeoRef (CAS Illumina)
- GeoScienceWorld GSW
- SpringerLink

Additional sources of information were sought and included:

- ISI Web of Science
- Google Scholar
- Government (i.e. United States, Canada, and Australia) and university websites and libraries (e.g., Arizona Water Protection Fund annual reports and grant reports, Australian Museum Scientific Publications, United State Forest Service publications, USDA Forest Service's TreeSearch)
- Published and unpublished reports (e.g., project monitoring reports, interviews, and agency report) were sought directly from individuals and organizations responsible for restoration projects (e.g., Ash Meadows National Wildlife Refuge, Grand Canyon Wildlands Council, the Museum of Northern Arizona, the National Park Service, Rocky Mountain Research Station, Southern Colorado Plateau I&M Network, USDA Forest Service, U.S. Geological Survey).

3.3 Study inclusion criteria

Criteria for inclusion of studies for this analysis involved relevance to the topic, interventions, and types of comparator, outcome, and study, as listed below:

- **Relevant subject(s):**
  Natural occurrences where aquifers meet the ground surface through seepage or fractures, classified as natural springs, in arid regions globally, including:
    - Riparian environments sourced from springs
    - Lakes/pools sourced from springs
    - Catchments
    - Watersheds
- **Types of intervention:**
  Hydrologic restoration techniques:
    - Check dams
    - Weirs
    - Weather stations

    - Watershed gauges

    Geomorphological and/or soil restoration techniques:
    - Channel relocation
    - Site re-contouring
    - Topsoil placement or removal

    Vegetation restoration techniques:
    - Seeding
    - Planting
    - Herbivore exclusion
    - Excavation of non-native species, such as Tamarisk and Russian Olive

    Historic fish distribution restoration:
    - Eradication of non-native fish species, including crayfish
    - Re-introduction of native fish species

    Modifications of adjacent areas:
    - Thinning or prescribed burning of adjacent forests to increase water yields
    - Reduction in groundwater withdrawals
    - Fencing enclosures to reduce access
    - Natural or anthropogenic erosion
- **Types of comparator:**
    - Experiments with controls (no intervention) and treatments (restoration)
    - Before-after studies
    - Before-after control-impact (BACI) studies
    - Interpretive models
- **Types of outcome:**

    Hydrologic outcomes such as changes in:
    - Water table level
    - Flow from springs
    - Duration and/or timing of flow
    - Natural or anthropogenic induced erosion

    Geomorphological and soil outcomes such as:
    - Channel presence and/or stability
    - Rockfall & slope processes
    - Integrity and restoration of soils

    Vegetation outcomes such as:
    - Species composition
    - Percent cover and architectural structure, biomass
    - Survival of planted material

    Invertebrate outcomes such as:
    - Species composition
    - Presence percentage

    Vertebrate outcomes for:
    - Fish, herpetofaunal, avifaunal, mammalian populations and habitat use
- **Types of study:**

Primary, peer-reviewed studies were considered to be the most dependable form of information. However, much of the available information exists in unpublished sources, such as theses and dissertations, monitoring reports, observational studies, and other types of literature.

Studies were initially considered by the title: if the title appeared to contain relevant inclusion criteria (i.e., relevant subjects and types of interventions) it was saved for further review. During this process, a count was maintained of how many titles were retrieved from each database, how many titles returned were duplicates, and how many met the inclusion criteria for further examination. This process identified 165 potentially relevant references.

Abstracts of studies considered relevant were read to determine if the studies met inclusion criteria and whether further examination would be useful. Reviewer bias was tested by kappa analysis by randomly selecting seventeen (10 %) of the potentially relevant studies for review by a second reviewer. The number of accepted and rejected studies, and discrepancies are summarized in Table 3. The kappa statistic was calculated using an online calculator (http://www.graphpad.com/quickcalcs/kappa1.cfm?K=2) to test for reviewer agreement (Table 3). The kappa score was calculated at 0.866, which is considered 'almost perfect' agreement between reviewers (Landis and Koch, 1977).

After papers with relevant abstracts were selected, the entire report was reviewed to verify the project's was relevance to the review. If the study was relevant, the study's data were retained for evaluation.

Table 3. Number of accepted and rejected studies by reviewers 1 and 2, and discrepancies for kappa analysis.

		Reviewer 2		
		Accept	**Reject**	**Total**
Reviewer 1	**Accept**	5	1	6
	Reject	0	11	11
	Total	5	12	17

3.4 Potential effect modifiers and reasons for heterogeneity:

Much heterogeneity exists across elevation and topography among arid regions, and under differing disturbance and land-use histories. Extensive heterogeneity within geomorphic microhabitats within springs (i.e., sloping bedrock surfaces, backwalls, channel terraces, and colluvial slopes). The manner(s) in which springs were restored also varied due to the extent of disturbance and management goals.

3.5 Study quality assessment

Pullin and Knight's (2003) hierarchy of evidence quality (HEQ) was used to determine whether studies will be included in the review, and all studies were assigned to one of the categories in Table 4. Evidence from Categories I through II-3 were included, while evidence that fell under Categories III was considered with caution. Evidence from Category IV was excluded, due to the lack of strong evidence.

Table 4. Hierarchy of Evidence Quality (modified by Pullin and Knight, 2003)

Category	Quality of Evidence
I	Strong evidence obtained from at least one properly designed; randomized controlled trial of appropriate size.
II-1	Evidence from well designed controlled trials without randomization.
II-2	Evidence from a comparison of differences between sites with and without (controls) a desired species or community.
II-3	Evidence obtained from multiple time series or from dramatic results in uncontrolled experiments.
III	Opinions of respected authorities based on qualitative field evidence, descriptive studies or reports of expert committees.
IV	Evidence inadequate owing to problems of methodology (e.g., sample size, length or comprehensiveness of monitoring) or conflicts of evidence.

3.6 Data extraction

Information of interest and data relevant to the question were summarized in a master spreadsheet (**APPENDIX A**) by one of the primary reviewers. Such information included the study's objectives, methods, and conditions of the study site pre- and post-restoration. This information was used to then determine quality of evidence, and ultimately restoration success. Once the data were summarized in the master spreadsheet, the studies were assigned to category of evidence quality (see section 3.5). Studies that were assigned to category IV were excluded for further examination. All other studies were then analyzed for restoration success.

3.7 Data synthesis

After compiling relevant information from each study and eliminating those assigned to a category IV quality of evidence, the reviewers completed a qualitative assessment of each project's restoration success based on the reported outcomes using the Society of Ecological Restoration (SER) International Science & Policy Working Group (2004) criteria for successful restoration (

TABLE 5). The reviewers determined if each criterion was met or not, and whether pre-stated objectives were accomplished or not for each of the studies analyzed. Studies were assigned a score based on how many criteria they met out of the nine total criteria. However, these scores may be misleading: not all criteria were the focus of restoration in all projects, and not all criteria could be assessed in all projects. Formal statistical meta-analysis was not used due to heterogeneity and variation in restoration designs and outcomes monitored.

Table 5. Attributes of a restored ecosystem, modified from the Society of Ecological Restoration International Primer on Ecological Restoration (Society for Ecological Restoration International Science & Policy Working Group, 2004).

Attribute	Criteria for Successful Restoration
1	Characteristic species assemblage similar to reference sites and provides suitable community structure.
2	Native species present to the greatest feasible extent.
3	Necessary functional groups for continued development and/or stability of restored ecosystem are represented, or have the potential to colonize naturally.
4	Sustainable physical environment for reproduction of species populations for desired conditions.
5	Normal functioning condition at stage of development with no signs of dysfunction.
6	Restoration is integrated into surrounding landscape.
7	No or limited threats from surrounding landscape to health and integrity of restored ecosystem.
8	Resilient to endure natural disturbances.
9	Self-sustaining to same degree as reference ecosystem.

4. Results

4.1 Review statistics

The literature search took place between September 3, 2009 and August 13, 2010, and gray literature reports were accepted until October 2010. Searches returned 433,299 titles, which were reviewed to locate relevant studies that addressed our main question. This review was limited to restored springs in arid regions. The full search results can be found in Appendix B. There were multiple steps in finding relevant articles, and the elimination process is shown in Table 6.

Table 6. Details of study elimination step process.

Elimination	No of studies
Studies captured from electronic databases (excluding duplicates)	433,299
Studies captured by other sources	21
Studies remaining after title elimination	165
Studies remaining after abstract elimination	35
Studies remaining after full text elimination	18
Studies remaining after Quality of Evidence elimination	15

4.2 Description of studies

Our investigation was designed to determine the outcomes from restoration treatments on hydrology, geomorphology, vegetation, and invertebrate/vertebrate species in arid regions. Except for one study, all of the springs restorations took place in the south-western United States. All of the sites had undergone some sort of disturbance, from alteration of the springs source(s) to general geomorphic degradation from grazing or other agricultural activities (**Error! Reference source not found.**). Restoration methods were tailored to each individual study's objectives and goals. The array of restoration methods is shown in **Error! Reference source not found.**. Hydrology was addressed by eight papers which reported on water quality and field parameters, such as discharge rate (**Error! Reference source not found.**). Invertebrate and vertebrate species were included as a focus in six papers. Nine papers, whose treatments varied from removal of structures to channel realignment, addressed geomorphology. Vegetation was addressed in all 15 papers. Of the 12 springs types classified by Springer and Stevens (2009), helocrene fens or wet meadow, hillslope, limnocrene, and rheocrene springs were the types found in the reference restoration reports (**Error! Reference source not found.**). Rheocrene springs were the most common.

4.3 Study quality assessment

All studies were categorized based on their quality of evidence. This eliminated studies that did not meet evidence quality standards outlined by Pullin and Knight (2003). One study was type II-1, seven were type II-2, one was type II-3, six were type III, and three were type IV (Table 7). Most of the studies did not include before-after impact studies or replicated restoration treatments. The studies that were classified as type IV were not considered for further examination (Appendix C).

4.4 Qualitative synthesis

Qualitative assessments produced varied results. Two studies included for analysis did not meet any of the criteria discussed by the SER International Science & Policy Working Group (2004). Two studies met two criteria out of nine, which were normal functioning and integrated, and integrated with limited or no threats. One study met three criteria, which included functional, sustainable, and integrated conditions. Three studies met four criteria out of the nine. Four met five criteria. Two studies met six criteria, and one study met eight total criteria. On average, the most criteria met were five out of nine. These results can be seen in Appendix D. We were unable to determine if all the criteria were met in some reports. Inclusion of additional information may have helped improve the accuracy of rating these studies.

Integration with the surrounding area was the criterion that was most often fulfilled for springs restoration projects. Sustainable reproduction and reduced or eliminated threats were the second most-often met criteria. The least-often met criteria included achievement of a characteristic assemblage, native species occurring to the greatest extent feasible, and restoration of normal ecological functioning.

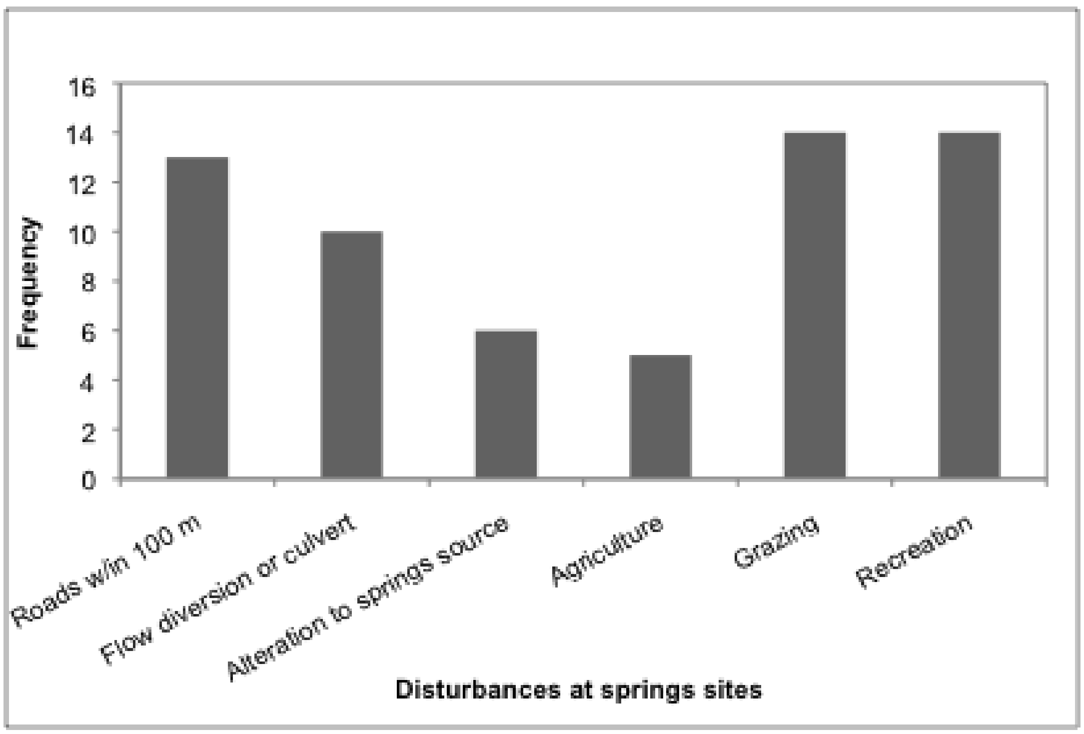

Figure 1. Frequency of disturbance types discovered at reviewed springs restoration studies.

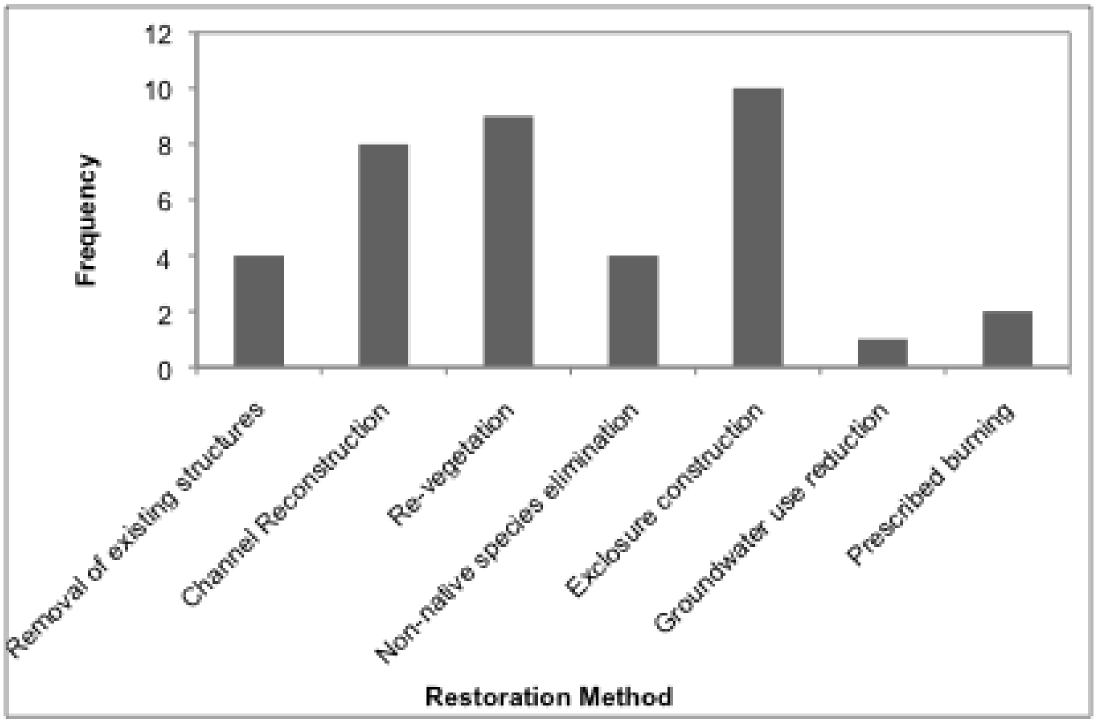

Figure 2. Frequency of restoration methods used in springs restoration studies.

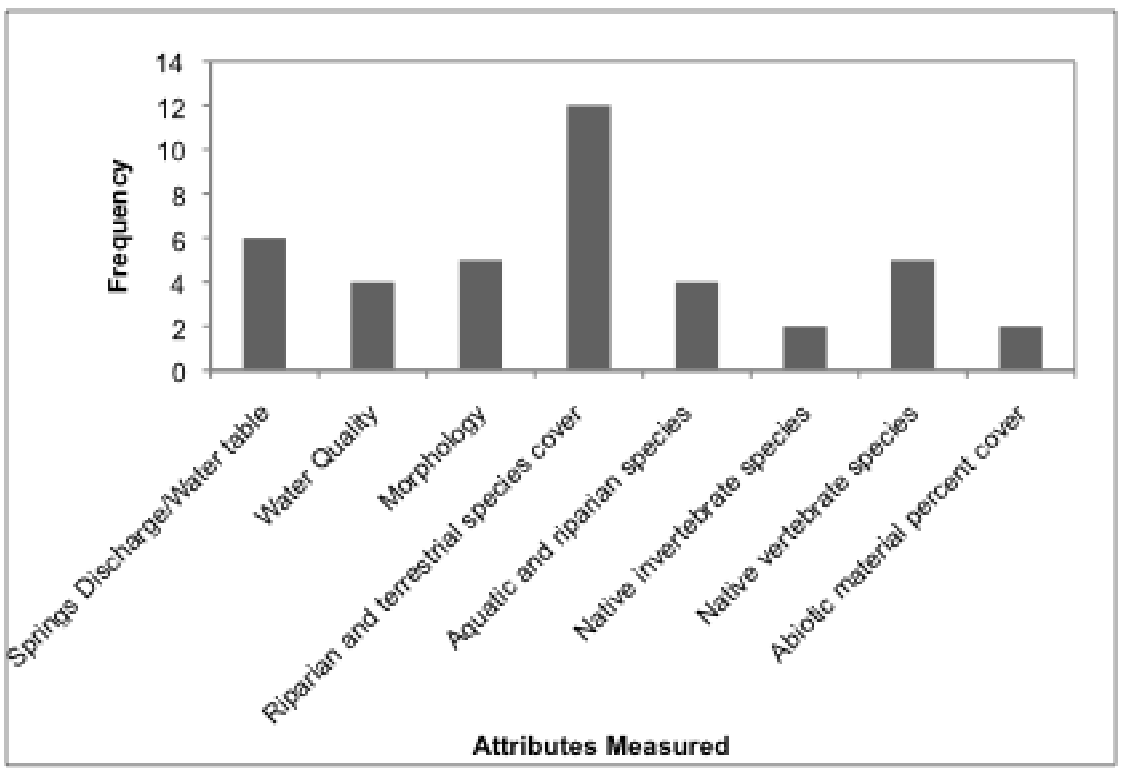

Figure 3. Frequency of attributes measured and monitored after springs restoration completion.

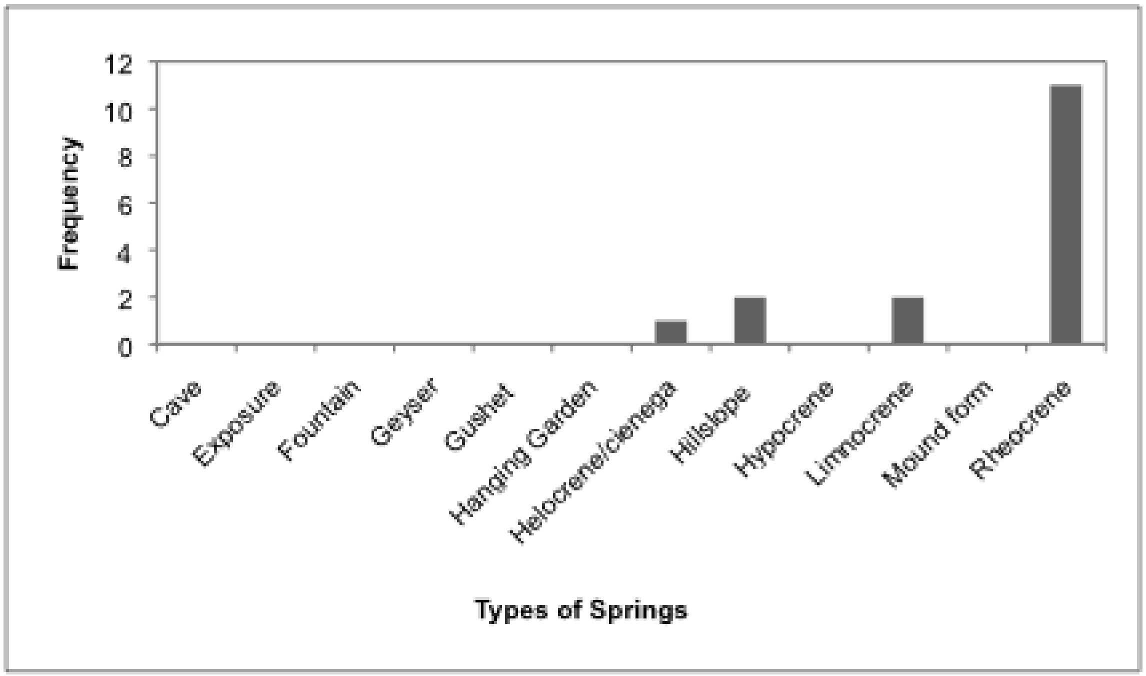

Figure 4. Frequency of springs sphere of discharge from restoration study references.

Table 7. Summary of study's restoration success.

Study	Study Category	Objectives met (yes or no)?	Scores	Percentage out of 9 criteria	Percentage of criteria able to evaluate
Anderson et al (2003), Clover Springs	II-2	Y	6	67%	67%
AWPF (2001), Bingham Cienega	II-2	Y	4	44%	80%
Brunson et al (2000), Muleshoe	II-2	Y	4	44%	57%
GCWC (2010) Pakoon Springs Rehabilitation Final Report	II-2	Y	8	89%	89%
Katz (2010), San Pedro Riparian Areas	II-2	Y	4	44%	57%
Kodric-Brown and Brown (2007), Ash Meadows Springs, NV and Dalhousie Spring, Australia	II-3	Y	0	0%	0%
Long and Endfield (2000), White Springs	III	Y	5	56%	100%
Long et al (2004), Soldier Springs	II-2	Y	6	67%	100%
Muelbauer et al (2009), Fossil Creek	II-2	Y	5	56%	100%
Natural Channel Design, Inc (2008), Brown Springs	III	N	0	0%	0%
Natural Channel Design, Inc (2008), Clover Springs	III	Y	5	56%	83%
Natural Channel Design, Inc (2008), Hart Prairie	III	Y	3	33%	50%
Natural Channel Design, Inc. (2008), Hoxworth Springs	III	Y	2	22%	40%
Springer et al (1999), Hoxworth Springs	II-1	Y	2	22%	100%
Weissenfluh (2007), Jackrabbit Springs	III	Y	4	44%	57%

Whether the studies met initial objectives also was considered in this assessment. To be achieved, objectives had to be stated *a priori* in the study. Results of this analysis were the most telling metric of project success among the restoration projects. From the 15 studies evaluated, only one did not meet the initially stated objectives (Table 7).

Because none of the studies accepted were based on either the HEQ or SER criteria, it was not surprising that their results did not precisely conform to those criteria. Nonetheless, finding this high rate of success is compelling evidence of general success of springs restoration efforts, and we regard this as the most revealing practical element of this study.

4.4.1 Evaluation of Evidence Quality

All studies were categorized based on their quality of evidence as described by Pullin and Knight (2003), but we found that their assessment approach underestimated project success. Several factors that limit the applicability of the quality of evidence approach include: 1) springs are highly individualistic ecosystems, each with a distinctive array of microhabitats, species, and ecological processes, such as disturbance regime; 2) pre-degradation information is often limited, and in the case of large springs prehistoric human use may have occurred over millennial time scales; 3) many springs are small (1-1000 m^2), with insufficient area for replication of treatment methods; 4) selected characteristics (e.g., a single species, or flow quantity) were often the target of restoration actions, rather than overall ecosystem health; and, 5) different microhabitats within springs require different restoration methods, sometimes limiting comparison of restoration methods. Therefore, springs restoration projects are rarely likely to fall into quality of evidence categories I or II-1, and most often fall into categories II-2 to III, in which the methods and outcomes rely upon the experience and opinions of respected professionals and the springs stewards (Figure 5). Relegation of springs restoration studies to lower levels of quality of information may generate greater likelihood of Type I statistical error, precluding the rating of assessment efforts as successful when they have been successful.

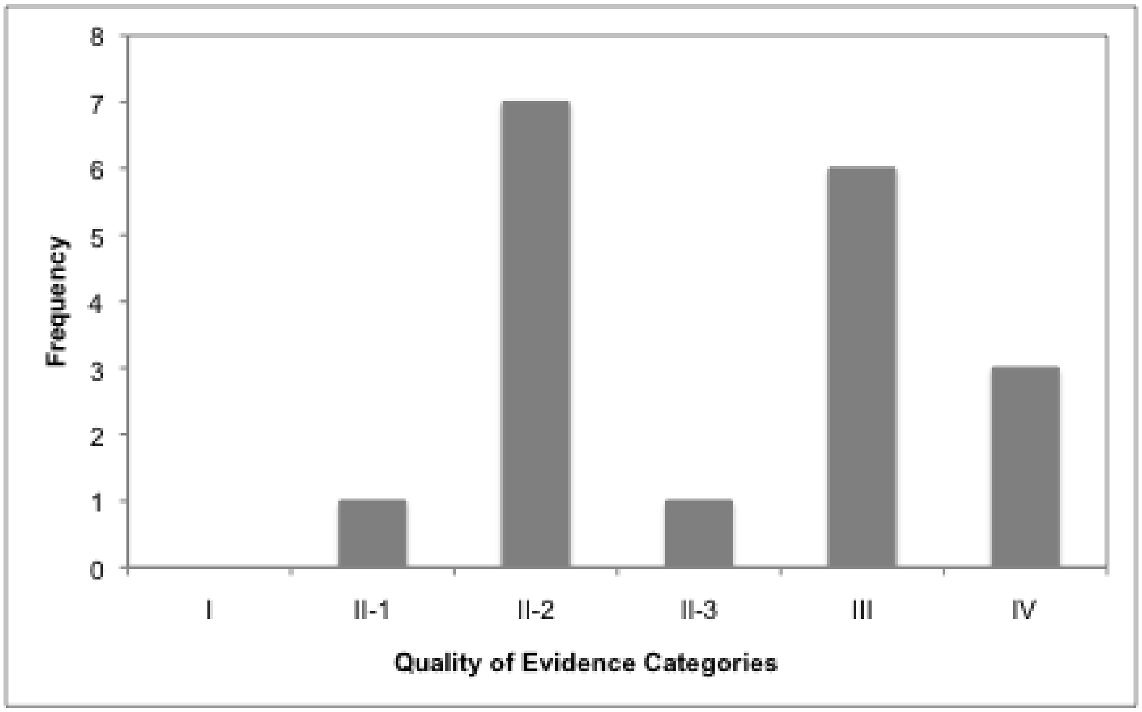

Figure 5. Frequency of Pullin and Knight's (2003) hierarchy of evidence quality rating for springs restoration projects.

4.4.2 Effectiveness in Restoring Springs Ecosystems

Determining the effectiveness of restoration efforts for hydrology, geomorphology, and plant and invertebrate/vertebrate species of springs ecosystems was difficult because not every springs restoration project reported all the outcomes of interest (Table 8). This distorted success ratings when using the SER (2004) criteria for successful restoration. Not every criterion was the focus of restoration effort, and the restoration success of each criterion could not necessarily be determined. Therefore, some studies may have received lower success ratings than the project actually achieved. When rating the successfulness of each restoration project by only the criteria that could be determined, the resulting scores were on average much higher (Table 7). As noted above, if restoration success was evaluated on the basis of whether the project achieved its objectives, 93 % of the projects were successful, which is a very high level of success. The success of meeting the project objectives were determined by whether the outcomes of the restoration indicated in the report matched *a priori* objectives, or if the report stated the objectives were successfully met.

Table 8. Outcomes monitored for each study.

Study	Outcomes monitored (yes or no)			
	Hydrology	**Geomor-phology**	**Invert/Vert Species**	**Vegetation**
Anderson et al (2003), Clover Springs	Y	Y	N	Y
AWPF (2001), Bingham Cienega	N	N	N	Y
Brunson et al (2001), Muleshoe	Y	Y	Y	Y
GCWC (2010) Pakoon Springs Rehabilitation Final Report	Y	Y	Y	Y
Katz (2010), San Pedro Riparian Areas	N	N	N	Y
Kodric-Brown and Brown (2007), Ash Meadows Springs, NV and Dalhousie Spring, Australia	Y	N	Y	Y
Long and Endfield (2000), White Springs	Y	Y	N	Y
Long et al (2004), Soldier Springs	N	Y	Y	Y
Muelbauer et al (2008), Fossil Creek	Y	Y	Y	Y
Natural Channel Design, Inc (2008), Brown Springs	N	N	N	Y
Natural Channel Design, Inc (2008), Clover Springs	N	N	N	Y
Natural Channel Design, Inc (2008), Hart Prairie	Y	Y	N	Y
Natural Channel Design, Inc (2008), Hoxworth Springs	Y	Y	N	Y
Springer et al (1999), Hoxworth Springs	N	N	N	Y
Weissenfluh (2007), Jackrabbit Springs	N	Y	Y	Y
Frequency:	8	9	6	15

4.5 Outcome of the review

4.5.1 Study Evidence Quality

Results of springs restoration projects were assessed either quantitatively, qualitatively, or both quantitatively and qualitatively (Table 9 9). Data analyzed quantitatively was considered to be more reliable than data assessed qualitatively.

Table 9. Data classification for studies reviewed.

Author(s):	**Data Qualitative or Quantitative?**	**Explanation**
Anderson et al., 2003	Qualitative and Quantitative	Used paired plots; Data were collected before (to establish baseline comparisons) and after restoration; Conducted geomorphic history analysis by historic photograph comparison; Profiles surveyed by total station; Percent aerial cover of plant species and abiotic material surveyed in rectangular plots.
Arizona Water Protection Fund, 2001	Qualitative and Quantitative	Conducted many statistical tests (X^2 and t-tests) calculating standard deviations and level of significance
Brunson et al., 2001	Quantitative	Conducted statistical tests (two-tailed probability level) pre- and post-restoration and over time; Significance level set at $p=0.05$.
Grand Canyon Wildland Council, Inc., 2010	Qualitative and Quantitative	Percent cover of each plant species in each polygon in four strata was determined in the field over time; water quality and flow were determined before and after; plant species richness, native cover, non-native plant species richness and cover, and vertebrate presence was noted.
Katz, 2010	Quantitative	Baseline data collected; Six restoration sites and six reference sites were used; Several vegetation metrics were compared between (1) perennial reference sites, (2) non-perennial reference sites, (3) Three Links Farm restoration sites, and (4) H&E Farm restoration sites; Differences were analyzed with t-tests using the Bonferroni adjustment for pair-wise comparisons.
Kodric-Brown and Brown, 2007	Qualitative	Authors indicate "surveys", but no details about the surveys; possibly fish counts.
Long and Delbin Endfield, 2000	Qualitative	Visual observations

Author(s):	Data Qualitative or Quantitative?	Explanation
Long et al., 2004	Quantitative	Field surveys: Channel measurements before and after treatment; longitudinal profile throughout the entire stream reach prior to placement of riffle formations; Pebble counts; Estimated number of trout per meter at the lower end of the treated reach by electro-shocking.
Muehlbauer et al., 2008	Quantitative	Leaf litter decomposition, macroinvertebrate community attributes, fungal biomass, and water quality and chemistry were compared before and after restoration above and below the dam; Experimental leaf decomposition rates were determined and compared using an equality of slopes test; A type I error rate of 0.05 was used for tests for effects of restoration on water quality and chemistry, leaf litter decomposition (P = 0.0181), fungal biomass (P = 0.0053), and macroinvertebrate community attributes (P = 0.0533 for abundance and P = 0.0546 for richness).
Natural Channel Design, Inc., 2008	Qualitative	Visible observations
Springer et al., 1999	Qualitative and Quantitative	Vegetation surveys before and after treatment; Channel geomorphology surveys before and after treatment
Weissenfluh, 2007	Qualitative	Visible observations

4.5.2 Hydrology

Hydrology was addressed in eight of the fifteen studies (Table 8). Rehabilitation of riparian and terrestrial vegetation affects the hydrology of springs ecosystems. Prescribed burns in the Muleshoe Ranch Watershed caused the percent cover of riparian tree overstory to increase, which presumably resulted in cooler water temperatures and great concentrations of dissolved oxygen, thus improving the aquatic habitat and watershed condition (Brunson et al., 2001). Rehabilitation of geomorphology (particularly the restoration of deeply incised channels) and the vigorous growth and expansion of riparian vegetation at Pakoon Springs have transformed that former ostrich ranch into a rich stand of creneoriparian habitat. Slightly reduced discharge reported in July 2009 and August 2010 at Pakoon Springs reflected vigorous vegetation growth, which was interpreted as success in native vegetation rehabilitation (Appendix E; Grand Canyon Wildlands Council, Inc., 2010). Reduced groundwater uptake in the San Pedro River was considered as a direct, beneficial effect, shaping streamside plant communities and increasing cover and species richness (Katz, 2010).

Kodric-Brown and Brown (2007) hypothesized that the removal of disturbance by large mammals detrimentally affected springs ecosystems because such disturbance helps maintain open-water habitats required by native fish and other species. After livestock exclusion, springs in Ash Meadows Wildlife Refuge sustained reduction in open-water habitat and fish populations, and Dalhousie Springs source pools became heavily overgrown with large quantities of dead and decomposing vegetation, creating anoxic water (Kodric-Brown and Brown, 2007). The large limnocrenes of Ash Meadows are almost all anthropogenic, and the natural configuration of the springs there was likely far more helocrenic than Kodric-Brown and Brown (2007) recognized. Nonetheless, springs in Grand Wash, north-western Arizona, that were fenced to exclude cattle, also sustained loss of surface water and endemic populations of the aquatic springsnail, *Pyrgulopsis bacchae* springsnails (Hydrobiidae; Grand Canyon Wildlands Council, Inc., 2002). From lessons learned at Ash Meadows (Otis Bay, Inc. and Stevens Ecological Consulting, LLC., 2005), we recommend that springs restoration projects should include consideration of the natural configuration of the springs, maintaining the natural disturbance regime (native animal grazing, flooding, rockfall/landslides, etc.), and monitoring microhabitat status and distribution.

Geomorphic restoration often requires reconfiguration of channels, terraces, and spring mound habitats. Re-development of a larger runoff channel outside of the low-flow channel, with meanders and banks, was reported to improve hydrological function at Hoxworth Springs in northern Arizona (Natural Channel Design, Inc., 2008). However, a log revetment structure along the slightly entrenched base-flow channel failed to stabilize the banks and, apparently because of the smooth nature of the wood, the structure may have resulted in increased flow velocity, producing localized channel scour. Monitoring and subsequent adjustment of structures (re-alignment of the channel and increasing the meander, instead of armouring a sharp turn) at Hoxworth Springs revealed that appropriate gradient and channel morphology could be used to restore springs outflow channels (AWPF, 2008).

The Fossil Springs watershed underwent major changes in geochemistry and hydrogeology after flow diversion removal, including: 1) increased water temperature below the dam; 2) total dissolved solids and specific conductance concentrations in the water below the dam became proportional to above-dam values; and 3) decreased pH values (Muehlbauer et al., 2009). These conditions better reflect the natural state of the creek's headwaters. Since the decommissioning of the Fossil Springs Diversion Dam and the reintroduction of stream flow to the natural channel, Fossil Springs has successfully begun to redevelop travertine dams, a natural stream formation that had deteriorated due to flow diversion.

4.5.3 Geomorphology

Geomorphologic restoration was addressed in nine of the studies, many of which reported increased channel stability after restoration [i.e., Hoxworth Springs (Natural Channel Design, Inc., 2008), Hart Prairie (Natural Channel Design, Inc., 2008), White Springs (Long and Endfield, 2000), Soldier Springs (Long et al., 2004), and Pakoon Springs (Grand Canyon Wildlands Council, Inc., 2010)]. These changes were in keeping with predefined project objectives and are reported as successful elements of springs restoration.

Creek channels at Muleshoe Ranch increased in maximum depth of pools, which are of interest for monitoring since they provide habitat of the Gila chub (*Gila intermedia;* Brunson et al., 2001). The increased depth of the pools was not attributed to increased stream flow (which actually decreased following restoration actions), but to changing channel morphology resulting from improvements to riparian vegetation as a result of the prescribed burning treatments (Brunson et al., 2001).

Channel stabilization positively influenced habitat quality at White Springs, the headwaters of Cibecue Creek, Arizona: check-dams built above and below the springs reversed channel downcutting, protecting the springs from large monsoon floods in July 1999 (Long and Endfield, 2000). Soldier Springs, also located on the White Mountain Apache Reservation in eastern Arizona, demonstrated significant improvement in channel morphology following the construction of riffle forming structures (Long et al., 2004); long pools have been maintained above the riffles and short pools below. The percentage of fine gravels, the preferred substrate for Apache trout (*Oncorhynchus apache*), doubled following those restoration efforts (Long et al., 2004).

Channel reconstruction by reshaping and redirecting the channel, and the use of low impact structures to encourage natural channel dynamics and stability, had little to no impact at Clover Springs in northern Arizona: Anderson et al. (2003) reported that longitudinal and cross-sectional profiles remained relatively similar there following geomorphic rehabilitation. However, maintaining the stream gradient was one of the project goals, and therefore the channel redesign was considered successful (Anderson et al., 2003).

4.5.4 Invertebrate and Vertebrate Species
Invertebrate and vertebrate species restoration was addressed in six studies. Positive changes were reported as increased population size, diversity, and density.

Gila chub (*Gila intermedia*) responded positively to the changes at the Hot Springs watershed in Muleshoe Ranch CMA. The Gila chub increased in density (chub capture/100 m haul), area, length of springs, and relative (percent) abundance in the fish community in comparison with pretreatment conditions (Brunson et al., 2001). These changes were dramatic considering the restoration consisted of only two types of treatments (reintroduction of periodic fires by prescribed burning and resting from animal grazing by construction of exclosures).

Kodric-Brown and Brown (2007) attributed the exclusion of feral livestock, implemented to restore habitats and stabilize populations of endangered species, caused vegetation overgrowth leading to 18 fish extinctions, mostly in smaller springs of Dalhousie Springs. Feral livestock had been excluded from Dalhousie Springs since 1995 (Kodric-Brown and Brown, 2007). Kodric-Brown and Brown (2007) also reported negative effects of excluding livestock in Ash Meadows, with many springs becoming heavily overgrown, causing the extinction of Cyprinodon pupfish. However, continuing restoration and maintenance efforts of Ash Meadows springs has led to increases in several native fish populations. Ash Meadows speckled dace (*Rhinichthys osculus nevadensis*) populations greatly increased, and Amargosa pupfish (*Cyprinodon nevadensis mionectes*) moved further downstream due to increased water temperatures after cattail removal and rechannelization of Jackrabbit Springs restoration efforts (Weissenfluh, 2007).

Flow reintroduction after diversion removal rapidly restored macroinvertebrate assemblage composition and structure at Fossil Springs and the homogeneity of the headwaters macroinvertebrate assemblage increased following restoration (Muehlbauer et al., 2009). However, the assemblage downstream from the dam in 2005 was still more dispersed than that above the dam (Muehlbauer et al., 2009). Muehlbauer et al. (2009) concluded that this suggests a time-lag between restoration and complete recovery, emphasizing the need for long-term monitoring of springs and runout channel restoration efforts.

Pakoon Springs restoration involved extensive geomorphic reworking, including removal of existing ostrich and cattle ranching structures, reconstruction of outflow channels, revegetation, removal of non-native species, and fencing to exclude undesired ungulates. Since this restoration effort, at least18 bird species have been detected, Gambel's quail (*Callipepla gambelii*) densities increased, and native aquatic macroinvertebrates, including dryopid beetles, colonized the restored channel (Grand Canyon Wildlands Council, Inc., 2010). Channel reconstruction, revegetation, and excluding livestock also improved Apache trout (*Oncorhynchus apache*) abundance at Soldier Springs in the White Mountains of Arizona (Long et al., 2004).

4.5.5 Plant Species

Restoration of native vegetation was an objective of all 15 studies, and all studies reported clear evidence of success.

Two reports addressed vegetation responses at the Clover Springs restoration site. Anderson et al. (2003) reported positive short-term changes in cover and biomass of native riparian and terrestrial species in study plots. Two months after channel restoration was completed in 2001, the restored riparian and terrestrial areas showed extensive increases in cover and biomass. However, revegetetation progress declined and percent cover of exposed mineral soil increased after a drought in 2002. Overall, proportion of riparian and terrestrial species improved, compared to pre-restoration conditions, but there was little change in species composition and non-native species still outnumbered native species. An ungulate exclosure constructed at Clover Springs helped protect the meadow, increasing natural recruitment and plant growth (Natural Channel Design, Inc., 2008).

Prescribed burn treatments in the Muleshoe Ranch Watershed were aimed at improving the overall watershed condition by reintroducing periodic fires. Increased instream cover, an important component of aquatic habitat that provides structural complexity and protective cover for fish, improved channel conditions at Muleshoe Ranch (Brunson et al., 2001). Total instream cover, which includes emergent, floating and overhanging vegetation, increased by 3.6-fold (p = 0.05) along monitoring transects (Brunson et al., 2001). In burned areas of the watershed, perennial grass experienced an increase in the total cover over pre-burn conditions after only two growing seasons suggesting that watershed condition had improved. In areas left unburned, perennial grass cover decreased. Brunson et al. (2001) hypothesized that when precipitation was average or above-average, burning would result in increased perennial grass cover after two growing seasons; whereas, when precipitation was below-average, perennial grass cover and abundance would be maintained after burning. Annual grasses increased after prescribed burns in both average and below-average rainfall years (Brunson et al., 2001). Though the results at the Muleshoe Ranch study are encouraging, the role of fire frequency and intensity in springs wetlands ecosystems is still generally poorly understood.

Recovery from intensive overgrazing by cattle, ostriches, and feral asses was rapid at Pakoon Springs, with recovery of damaged vegetation and rapid growth of planted native phreatophytes (Grand Canyon Wildlands Council, Inc., 2010). Monitoring there demonstrated considerable natural recruitment, vigorous growth of pre-existing vegetation, and low mortality of natural and planted vegetation in all five springs arenas. Continued removal of non-native tamarisk (*Tamarix spp.*), mosquitofish (*Gambusia affinis*), and bullfrogs (*Rana catesbeiana*) is on-going in that restoration project.

The effects of grazing on the restored riparian corridor of Hoxworth Springs were evaluated, and vegetation there was compared with that in three different types of exclosures: “total exclosure” (no grazing ungulates), “cattle exclosure” (exclosed to cattle but open to elk), and “total grazing” (open to both cattle and elk grazing; Godwin, 2004; Springer et al., 1999). There were no significant differences detected in the mean percent vegetative cover, plant species diversity, or native plant population structure between treatment types; however, qualitative observations indicated a positive correlation between the degree of exclosure and biomass produced (Godwin, 2004; Springer et al., 1999). Godwin (2004) concluded that potential positive changes were not detectable in the brief duration of analysis, and that continued monitoring was needed to reveal long-term success. Climate variability in the Southwest makes it difficult to understand short-term population dynamics. Springer et al. (1999) also observed that inconsistent vegetation monitoring methods affected perceived outcomes of the restoration over the short period of monitoring after the restoration treatments.

Protective fencing, and elevated water levels from rock and gravel riffle formation construction improved vegetation at Soldier Springs. Transplanted sedges along the streambed of the Soldier Springs outflow channel were reported to begin to spread along the edges of the banks and became interwoven with aquatic vegetation (Long et al., 2004).

5. Discussion

Although this review was meant to prevent bias in the search methods, few springs restoration studies were found outside of the United States. Two papers were found in regards to springs in China, but these reports did not fit our inclusion criteria and were eliminated during the ‘abstract elimination’ stage. It appears that the majority of springs restoration projects have been carried out in United States.

This review also revealed that many studies did not incorporate before-after impact studies or replicated restoration treatments. This is likely due to the general absence of information on the pre-exploitation condition of most springs, many of which have been used by humans for centuries or millennia. In addition, the limited size and unique nature of springs ecosystems often prevents adequate within-site replication. The lack of before-after impact studies and replicated restorations make it difficult to ultimately determine if disturbed springs have been restored to conditions comparable to that of non-disturbed springs.

Finally, this review demonstrated that many different restoration methods are used, depending on conditions at individual springs. Projects included in the study involved both partial and full ecosystem restoration. However, in both cases, restoration efforts produced desired changes in springs ecosystem conditions.

Development and use of comprehensive springs inventory and monitoring protocols are beginning to be standardized, a process that has been delayed by the lack of a lexicon about springs types, inadequate mapping, and insufficient comprehensive inventory and assessment data (Stevens and Meretsky, 2008; Springs Stewardship Institute, 2011). These problems are exacerbated by the great diversity of springs types, the cross-disciplinary nature of springs research, and the multiple, uncoordinated administrative contexts under which researchers and land managers operate. Lack of scientific study and conservation has limited the knowledge available to develop and implement appropriate springs restoration theory and restoration protocols.

5.1 Hydrology and Geomorphology

Geomorphic restoration, as discussed previously, involves many different and site-specific approaches. Many of the studies reviewed reported positive changes occurring at restored springs site as a result of geomorphic rehabilitation. For example, geomorphic restoration methods at Pakoon Springs included: 1) recreating spring mounds/hillside seeps and outflow channels; 2) removal or reduction of berms constructed by previous owners; and 3) eliminated roads and reshaping the landscape around spring sources. These activities at Pakoon Springs revealed that when the regional aquifer is intact, springs ecosystem geomorphology and habitat rehabilitation can be achieved (Grand Canyon Wildlands Council, Inc., 2010). Restructuring riffles at Soldier Springs provided rehabilitated channel habitat, forms that achieved habitat recovery better than did log structures (Long et al., 2004). Restoration stewards at Soldier Springs also observed that multiple treatments practiced together (i.e., riffle formations, protective fencing, and vegetation transplanting) contributed to overall project success. Check dam construction in White Springs outflow channel increased bank stabilization and reversed downcutting (Long and Endfield, 2000). In addition, natural geomorphic processes were restored following removal of diversion structures: natural travertine channel forms began to rebuild after removal of diversion from Fossil Springs. Therefore, geomorphologic restoration can substantially improve the hydrology of altered springs ecosystems.

5.2 Invertebrate and Vertebrates Species

Many of the restoration methods, such as geomorphic rehabilitation, diversion removal, and revegetation, directly and indirectly contributed to population rehabilitation of target and non-target invertebrate and vertebrate springs species. For example: 1) Recontouring eliminated non-native bullfrogs from several restoration arenas at Pakoon Springs (Grand Canyon Wildlands Council, 2010); 2) Native chub (*Gila* spp.) and other fish populations increased at Muleshoe Ranch after prescribed burning of upland areas (Brunson et al., 2001); 3) Native Apache Trout (*Oncorhynchus apache*) abundance rebounded at Soldier Springs as a result of the preferred substrate reforming (Long et al., 2004). Finally, removal of diversion structures enhanced macroinvertebrate populations at Fossil Springs (Muehlbauer et al., 2008).

5.3 Vegetation

Vegetation restoration treatments included: 1) planting native seeds and transplants; 2) removing non-native species; 3) excluding large ungulates to promote vegetation recovery; and, 4) reducing vegetation abundance by prescribed burning.

Lessons learned during the restoration of Kings, Point of Rocks, and Upper Jackrabbit Springs in Ash Meadows National Wildlife Refuge helped guide additional restoration projects in Ash Meadows. Restoration at Jackrabbit Springs involved construction of the largest native vegetation planting and drip irrigation system ever created for the survival of transplanted vegetation in the arid area (Weissenfluh, 2007). Hot and windy climates are highly stressful for transporting and planting native vegetation. It is advantageous to acclimate transplanted plants prior to planting. The Jackrabbit Springs restoration project also demonstrated the importance and cost effectiveness of regular monitoring, and though such activity was to detect downturns in the recovery process, fixing problems before they jeopardized project success.

Excluding livestock proved beneficial to vegetation at Pakoon Springs (Grand Canyon Wildlands Council, Inc., 2010) and at Hoxworth Springs (Natural Channel Design, Inc., 2008): at the latter site, wetland vegetation cover rebounded after elk and cattle exclosure fence was installed. Brown Creek riparian restoration managers observed that restricting mammal access reduced further springs ecosystem degradation from trampling and browsing. Buck and pole fencing was discovered to not hold up well, and was therefore not effective in restricting feral livestock, cattle, non-native elk, and recreational access to Hoxworth Springs (Natural Channel Design, Inc., 2008).

Prescribed burning treatments within the Muleshoe Ranch CMA demonstrated that periodic burns kept shrub cover at desired levels, while a single prescribed burn killed only a portion of the undesirable vegetation and surviving shrubs recovered quickly (Brunson et al., 2001). Burning effects varied among vegetation types: junipers were less affected than other common shrubs (i.e., shindagger, acacia, mesquite, and snakeweed; Brunson et al., 2001). Brunson et al. (2001) further demonstrated that even during droughts, burning resulted in increased grass abundance and cover. However, they recommended allowing time for grasses to recover before livestock were re-introduced and also recommended monitoring regrowth closely. The benefits of resting the landscape from grazing and using prescribed burning led to overall watershed improvement and recovery of native fish populations at Muleshoe Ranch.

6. Conclusions

We encountered several challenges in addressing whether projects in arid lands have been effective in restoring hydrology, geomorphology, and plant and invertebrates species composition comparable to conditions of natural springs with minimal anthropogenic disturbances: 1) The scope of restoration efforts varied from “fixing” specific problems to “whole ecosystem” restoration. Some restoration efforts focused solely or primarily on native vegetation restoration or on non-native species removal, rather than on ecosystem-level restoration of flow, geomorphology, flora, and fauna. In such cases, the restoration project may achieve its objectives, but fall short of full restoration. 2) Restoration reference conditions and goals may not be unambiguously defined – in some cases human impacts to springs may have taken place over centuries or millennia. This may restrict the comparative approach and use of controls to evaluate restoration success. This restriction may be alleviated by careful study of the pre-treatment condition, though comparison of the restoration site with similar springs in the region, and by careful selection of appropriate monitoring elements that span the scope of the restoration goals. 3) Springs are uniquely individualistic ecosystems, sometimes containing multiple microhabitats, and no two springs are precisely alike. Insufficient ecological analyses have been accomplished on many springs types to fully understand them as ecosystems. The expectations, strategies, and outcomes of restoration is likely to vary within and among springs types, influencing the costs and scheduling of interventions. 4) Ecosystem response variables varied among projects: not all variables were monitored at all restoration sites, limiting comparison among projects. 5) Qualitative tools used for evaluating project success (e.g., the SER criteria for successful restoration) were of limited use in broad-scope evaluation of springs restoration because most projects were small, single-site restoration efforts at different types of springs. This caused us to rely on evaluation of success in relation to stated project goals. While levels of success were reportedly high, 6) such reporting was not systematic, and often depended more on policy requirements of the funding entity rather than on ecosystem characteristics. Overall, both the science of springs ecosystem ecology and assessment of restoration success will benefit from more systematic analysis.

Fortunately, restoration practitioners are beginning to recognize these issues and limitations, and a broader perspective of springs ecosystem ecology is being incorporated into all aspects of springs inventory, assessment, restoration planning, and implementation (Springs Stewardship Institute, 2011). We hope this review increases general awareness of the challenges facing evaluation of project success, and contributes to increased consistency of springs ecosystem restoration and monitoring.

6.1 Implications for Management

Additional basic and applied research in the ecology and restoration of arid land springs will help improve understanding of these productive, diverse, and highly threatened habitats. How and to what extent different types of springs and associated microhabitats can be restored will vary based on project starting conditions, but an insufficient number of restoration projects of individual springs types exists from which to extract such insights. When more restorations have been conducted, springs stewards will be better able to predict appropriate treatments, costs, challenges, and outcome benefits among different types of microhabitats within springs and among different types of springs ecosystems.

Post-restoration monitoring and long-term information management are essential for understanding the cost, duration, extent, and effectiveness of ecosystem recovery. Development of more codified monitoring protocols, such as those under development by Springer et al. (2008) and those currently under development by the U.S. Forest Service will be useful for comparison of restoration success among projects.

Few regions have sufficient basic information on the distribution of springs types (

Table **1**) to formulate prioritized conservation recommendations, particularly for rare types of springs. We recommend that basic inventories be conducted within land units and states to identify rare springs types, and focus restoration on the most threatened types. This is both a management and a research issue. If performed systematically, such an effort can yield consistent, comparable results across broad geographic areas and provide highly useful data on the restoration of various springs types.

6.2 Implications for Research

Unlike large river, lake, or landscape restoration programs, springs restoration efforts usually involve relatively well-defined efforts by small groups of stakeholders to achieve one or a few focused goals. Springs restoration is a newly developing area of conservation action, and the tools for evaluating project success are still under development (Springs Stewardship Institute, 2011). Development of a systematic quality assessment protocols and a restoration success rating system, specifically for small and individualistic ecosystems, will enhance quality and success assessments of studies like those examined in this review.

Better documentation of springs restoration projects and more systematic methods for reporting outcomes also will improve analysis of springs restoration projects. Until this type of documentation becomes available, we recommend using the qualitative sociological approach of rating springs ecosystem restoration success in relation to stated goals. Improved mathematical tools for evaluation of non-replicated, single-site restoration are outstanding and will develop through more extensive statistical analyses; however, such efforts will require a far larger sample size than presently exists. Nonetheless, guidance on restoration assessment protocols and trend assessment following treatment should be widely available to springs stewards interested in planning and implementing springs restoration and monitoring (e.g., Springs Stewardship Institute, 2011). We encourage springs stewards to consider these issues and how results of their restoration and monitoring projects can be compared with other similar efforts, thereby contributing to the growth of this field and expansion of the science of springs ecosystem ecology.

7. Acknowledgements

We thank the Ecological Restoration Institute of Northern Arizona University for funding this project, and the Museum of Northern Arizona for supporting L.E. Stevens work. We also like to thank the numerous individuals and agencies that helped supplement our review with unpublished literature, and who include but are not limited to: Kelly Burke of the Grand Canyon Wildlands Council, Inc. in Flagstaff; Dick Flieshman of the United States Forest Service, Coconino National Forest Supervisor’s Office; Julia Fonseca from Pima County, Arizona; Gerald J. Gottfried, Research Forester at the Rocky Mountain Research Station; Stephen Tighe of the Arizona Water Protection Fund; and Darrick Weissenfluh from Ash Meadows National Wildlife Refuge; and We also thank Peter Z. Fulé from the School of Forestry and the Ecological Restoration Institute at Northern

Arizona University for suggesting analytical techniques, and to Jeri Ledbetter of the Springs Stewardship Institute in Flagstaff for insight into restoration information management. We also thank Elizabeth L. Kalies from the Ecological Restoration Institute for her review of this work. Finally, we recognize and laud the many hard-working springs restoration practitioners whose dedicated work made this review possible.

8. Potential Conflicts of Interest and Sources of Support

The Ecological Restoration Institute of Northern Arizona University supported this project, with assistance from the Museum of Northern Arizona. The reviewers know of no conflicts of interest.

9. References

Anderson, D., Springer, A., Kennedy, J., Odem, W., DeWald, L., Fleishman, D., 2003.Verde River Headwaters Restoration Demonstration Project: Final Report, Arizona Department of Water Resources Water Protection Fund, Grant No. 98-059.

Arizona Water Protection Fund, 2001. Bingham Cienega Riparian Restoration Project, Final Report, Grant # 97-040WPF, Pima County, AZ.

Arizona Water Protection Fund, 2008. Hoxworth Springs Stream Channel Restoration Project: Executive Summary, AWPF Grant #08-159WPF, Retrieved March 7, 2011 from: www.adwr.state.az.us/awpf/pubs/FY2008/WPF0364.pdf.

Blinn, D.W., 2008. The extreme environment, trophic structure, and ecosystem dynamics of a large, fishless desert spring. In Aridland Springs in North America: Ecology and Conservation, ed. L.E. Stevens, V.J. Meretsky, pp. 98-126. University of Arizona Press, Tucson.

Brock, T.D., 1994. Life at High Temperatures. Yellowstone Association, Yellowstone National Park, Wyoming.

Brune, G., 1981, Springs of Texas, Volume 1, Fort Worth, TX, Branch-Smith, Inc., 566 .

Brunson, E., Gori, D., Backer, D., 2001. Watershed improvement to restore riparian and aquatic habitat on the Muleshoe Ranch CMS, Final Report, The Nature Conservancy, AWPF Project Number 97-035.

Cantonati, M., Gerecke, R., Jüttner, I., Cox, E.J. (eds.), 2011. Springs: neglected key habitats for biodiversity conservation. Journal of Limnology 70, 1-87.

Godwin, T.N., 2004. Evaluation of Streambed Restoration and Occurrence of Hoxworth Springs, Coconino County, Arizona [Master’s thesis]: Northern Arizona University, 191.

Grand Canyon Wildlands Council, Inc., 2002. A hydrological and biological inventory of springs, seeps and ponds of the Arizona Strip, Final Report, Arizona Department of Water Resources, Water Protection Fund, Phoenix, AZ.

Grand Canyon Wildlands Council, 2003. Biological inventory and assessment of ten south rim springs in Grand Canyon National Park: final report. Grand Canyon Science Center, National Park Service Contract WPF-230.

Grand Canyon Wildlands Council, Inc., 2010. Pakoon Springs Rehabilitation, Final Report, Task #9, AWPF Grant Contract #06-137WPF, Flagstaff, AZ.

Habermehl, M.A., 1983. Hydrogeology and hydrochemistry of the Great Artesian Basin, Australia. In Proceedings, International Conference Groundwater and Man, Sydney, 1983, Australia Water Resource Council Conference Series 8(3), 83-98. Australia Government Publication Service, Canberra.

Hendrickson, D.A., Minckley, W.L., 1984. Cienegas: Vanishing climax communities of the American Southwest, Desert Plants 6(3), 130-175.

Huntoon, P., 1974. The karstic ground water basins of the Kaibab Plateau, Arizona. Water Resources Research 10, 579-590.

Hynes, H.B.N., 1970. The ecology of running waters. University of Toronto Press, Toronto

Katz, G., 2010. Revised Final Report: Test of Riparian Recovery Following Reduced Groundwater Pumping, Lower San Pedro River, AWPF Grant #08-151WPF, Appalachian State University, Boone, NC.

Kodric-Brown, A., Brown, J.H., 2007. Native fishes, exotic mammals, and the conservation of desert springs, Frontiers in Ecology 5(10), 549-553.

Kresic, N., Stevanovic, Z., 2010. Groundwater Hydrology of Springs. Elsevier, Burlington.

Landis, J.R., Koch, G. G., 1977. The measurement of observer agreement for categorical data. *Biometrics* 33, 159-174.

Ledbetter, J.D., Stevens L.E., Springer A.E., 2010. In press. Springs Inventory Database.

Lin, J.Y., Chen, C. F., Lei, F. R., Hsieh, C. D., 2010. Field observations and management strategy for hot spring wastewater in Wulai area, Taiwan, Water Science and Technology 61.9.

Long, J.W., Burnette, B.M., Medina, A.L., Parker, J.L., 2004. Restoration of Soldier Spring: and isolated habitat for native Apache trout. In Proceedings, International Conference, 16th, Victoria, Canada, Society for Ecological Restoration, 1-5.

Long, J.W., Endfield, D., 2000. Restoration of White Spring. In Proceedings, USDA Forest Service Rocky Mountain Research Station-P-13, 359-360.

Lund, J.W., 1995. Historical Impacts of Geothermal Resources on the People of North America, Geo-Heat Center Bulletin, 7-14.

Macholl, J.A., 2007. Inventory of Wisconsin's springs. Wisconsin Geological and Natural History Survey, Madison.

Meinzer, O.E., 1923. Outline of ground-water hydrology, with definitions. US Geol Survey Water Supply Paper 494.

Monroe, S.A., Antweiler, R.C., Hart, R.J., Taylor, H.E., Truini, M., Rihs, J.R., Felger, T.J., 2005. Chemical characteristics of ground-water discharge along the south rim of Grand Canyon in Grand Canyon National Park, Arizona, 2000-2001. U.S. Department of the Interior Scientific Investigations Report, 2004-5146.

Muehlbauer, J.D., LeRoy, C.J., Lovett, J.M., Flaccus, K.K., Vlieg, J.K., Marks, J.C., 2009. Short-term responses of decomposers to flow restoration in Fossil Creek, Arizona, USA. Hydrobiologia 618, 35–45.

Natural Channel Design, Inc., 2008. AWPF Grant Projects Evaluation, Phase II: Case Studies, Final Report. Arizona Water Protection Fund, Phoenix, AZ.

Odum, H.T., 1957. Trophic structure and productivity of Silver Springs, Florida, Ecological Monographs 27, 55-112.

Otis Bay, Inc. and Stevens Ecological Consulting, LLC., 2005. Hines Springs Mitigation Draft Phase I Report. Los Angeles Water and Power and Inyo County Water District, California.

Perla, B.S., Stevens, L.E., 2008. Biodiversity and productivity at an undisturbed spring in comparison with adjacent grazed riparian and upland habitats. In Aridland Springs in North America: Ecology and Conservation, ed. L.E. Stevens, V.J. Meretsky, pp. 230-243. University of Arizona Press, Tucson.

Ponder, W.F., 2002. Desert Springs of the Australian Great Artesian Basin. In Proceedings, Spring-fed Wetlands: Important Scientific and Cultural Resources of the Intermountain Region, 1-13.

Pringle, C.M., Triska, F.J., 2000. Emergent biological patterns and surface-subsurface interactions at landscape scales. *In* Streams and Ground Waters, ed. J.B. Jones, P.J. Mulholland, Academic Press, San Diego.

Pullin, A.S., Knight, T.M., 2003. Support for decision making in conservation practice: An evidence-based approach. Journal for Nature Conservation 11, 83-90.

Society for Ecological Restoration International Science & Policy Working Group, 2004. The SER International Primer on Ecological Restoration, www.ser.org & Tucson: Society for Ecological Restoration International.

Springer, A., Godwin, T., DeWald, L., Hink, J., 1999. Final Project Progress Report Arizona Water Protection Fund Grant No: 96-0003WPF. Arizona Department of Water Resources, Water Protection Fund.

Springer A.E., Stevens, L.E., Anderson, D.E., Parnell, R.A., Kreamer, D.K., Levin, L., Flora, S., 2008. A comprehensive springs classification system: integrating geomorphic, hydrogeochemical, and ecological criteria. In Aridland Springs in North America: Ecology and Conservation, ed. L.E. Stevens, V.J. Meretsky, pp. 49-75. University of Arizona Press, Tucson.

Springer, A.E., Stevens, L.E., 2009. Spheres of discharge of springs. Hydrogeology Journal 17, 83-93.

Springs Stewardship Institute, 2011. Springs Stewardship. Flagstaff, AZ. Retrieved August 28, 2011 from: www.springstewardship.org.

Stevens, L.E., Meretsky, V.J., 2008, Aridland Springs in North America: Ecology and Conservation. University of Arizona Press, Tucson.

Thompson, B.C., Matuski-Rowan, P.L., Boykin, K.G., 2002. Prioritizing conservation potential of arid-land montane natural springs and associated riparian areas. Journal of Arid Environments 5, 527-547.

Unmack, P.J., Minckley, W.L., 2008. The Demise of Desert Springs, In Aridland Springs in North America: Ecology and Conservation, ed. L.E. Stevens, V.J. Meretsky, pp.11-34. University of Arizona Press, Tucson.

Weisberg, P.J., Sunderman, S.O., Karam, S.L., 2010, Fire Patterns and Fire Effects on the Plant Community, Ash Meadows National Wildlife Refuge. U.S. Fish and Wildlife Service Ash Meadows National Wildlife Refuge, Amargosa Valley.

Weissenfluh, D., 2007. The Upper Jackrabbit Restoration (Phase 1) Site Step-by-Step Report Ash Meadows National Wildlife Refuge Nye County, Nevada, Compiled By: Quantell, Inc. for the U.S. Department of Interior, U.S. Fish and Wildlife Service Ash Meadows National Wildlife Refuge.

Welsh, S.L., 1989. On the distribution of Utah's hanging gardens. Great Basin Naturalist 49, 1-30.

Appendix A. Master spreadsheet used in summarizing restoration projects.

Author(s):		
Publication Year:		
Restoration Project Name:		
Prepared For:		
Involved Agencies:		
Study Objective:		
Springs Descriptions:	Name(s):	
	Type(s):	
	Location(s):	
Restoration Methods:		
Focused Site Measurements:		
Target Species:		
Pre-Intervention Impacts/Disturbances (yes/no):	Roads w/in 100 m?	
	Flow diversion or culvert?	
	Alteration to springs source?	
	Agriculture?	
	Grazing?	
	Recreation?	
Intervention(s) (i.e., Restoration Recommendations/Actions):		
Replication or Previous restoration actions/recommendations:		
Baseline comparison (yes/no)?		
Intra-treatment variation:	Positive Changes:	
	Negative Changes:	
Measured impacts of restoration:		
Successful restoration measurements:		
Year Restoration Complete:		
Year Monitoring/follow-up completed:		
Duration of Monitoring:		
Number of times monitored:		
Post-restoration actions/assessments:		
Objectives Met (yes/no)?		
Quality Assurance measures (quality control methods/protocols used):		
Study Evidence Quality Category (Pullin & Knight 2003)		

Appendix B. Search results displaying databases utilized, dates searches took place, and total titles returned and number of duplications before elimination process.

Search terms to include all combinations of the following:

- Springs* and
- Restoration, hydrology#, prescribed burns§, management, geomorphologyϒ (or erosion, or sedimentation, or channel), conservation, fencing†, diversion, stabilization.

* -OR- Natural Springs -OR- Riparian Springs -OR- Watersheds -OR- Catchments
\# -OR- Hydrogeology
§ -OR- Natural Fire -OR- Wildfire
ϒ -OR- Erosion -OR- Sedimentation -OR- Channel
† -OR- Enclosures

Summary:

Search databases utilized	**Date(s) Searched**	**Total number of titles retained for further examination (abstract/full-text elimination) (excluding duplicates)**
Science Direct	9/3/2009-9/16/2009, 12/23/2009, 8/13/2010	39
NAU Cline Library (generic search resulted in papers from GeoRef and SpringerLink)	9/15/2009	8
GeoRef (CAS Illumina)	9/15/2009, 12/23/2009-12/29/2009, 8/13/2010	46
GeoScience World	9/13/2009, 12/29/2009	1
SpringerLink	12/29/2009	1
JSTOR	9/13/2009, 12/30/2009, 1/5/2010, 1/6/2010, 8/13/2010	21
ProQuest	1/6/2010, 8/13/2010	3
Academic Search Complete	1/11/2010, 8/13/2010	3
ISI Web of Science	1/11/2010, 8/13/2010	2
Google Scholar	1/11/2010, 1/12/2010, 8/13/2010	14
Arizona Water Protection Fund Online Documents and Reports	1/27/2010	3

1) ScienceDirect

Search	Total	Chosen by Title	Dups	Titles not returned before	Total for Possible Use
Sept 3rd, 2009					
Springs* AND Restoration AND Riparian	1232	6	0	0	6
Sept 8th, 2009					
Springs* AND Wildfire AND Restoration (returned many papers relating to restoration of trees/ponderosas, plants & wildlife, but not our topic)	502	9	2	7	7
Sept 16th, 2009					
Fire AND Ponderosa AND Forests	94	5	1	4	4
Fire AND debris flow AND watershed	897	10	3	7	7
Dec. 23rd, 2009					
Springs* AND Restoration AND Conservation (limited search to journals: Forest Ecology and Management, Journal of Arid Environments, Geomorphology, Journal of Hydrology, Journal of Environmental Management, which eliminated books)	6007/reduced to 721 after refined.	14	0	14	14
Springs* AND Restoration AND Hydrology	1955	4	4	0	0
Springs* AND Prescribed burns§	494	1	0	1	1
Springs* AND Restoration AND erosion AND sedimentation AND channel AND stabilization AND geomorphology	131	0	0	0	0
Springs* AND Restoration AND hydrogeology	278	0	0	0	0
Springs* AND management AND fencing AND conservation	577	0	0	0	0
Aug. 13th, 2010					
Springs* AND management AND restoration	1625	4	1	3	3
Springs* AND riparian AND restoration (was important to hyphenate 'arid-land' springs; ‘arid land’ did not return any results)	404	1	1	0	0

2) GeoRef (CAS Illumina)

Search	Total	Chosen by Title	Dups	Titles not returned before	Total for Possible Use
Sept 15th, 2009					
Springs* AND restoration AND Prescribed burns§	0	-	-	-	-

Search	Total	Chosen by Title	Dups	Titles not returned before	Total for Possible Use
Springs* AND climate change AND Prescribed burns§	1	0	0	1	0
Dec. 23rd, 2009					
Springs* AND restoration OR conservation OR management	3392	13	0	13	13
Dec. 27th/28th, 2009					
Springs* AND restoration OR conservation OR management AND Hydrology OR Erosion OR Sedimentation	1815	24	6	18	18
Dec. 28th, 2009					
Springs* AND Prescribed burns§ AND Fencing†	0	0	0	0	0
Springs* AND Channel AND Geomorphology	446	4	3	1	1
Springs* AND Restoration AND Stabilization	27	2	0	2	2
Springs* AND Restoration AND Hydrology	165	16	11	5	5
Dec. 29th, 2009					
Springs* AND Conservation AND Stabilization	17	1	1	0	0
Springs* AND Management AND Geomorphology	329	7	3	4	4
Springs* AND Restoration AND Conservation OR Management	316	14	11	3	3
Springs* AND Restoration AND Hydrogeology	101	6	6	0	0
Aug. 13th, 2010					
Arid-land Springs AND Riparian AND Restoration	0	0	0	0	0
Arid-land Springs AND Riparian AND Restoration AND Management	0	0	0	0	0

3) GeoScienceWorld GSW

Search	Total	Chosen by Title	Dups	Titles not returned before	Total for Use
Dec. 29th, 2009					
Springs* AND Restoration	822	5	3	0	0

4) SpringerLink

Search	Total	Chosen by Title	Dups	Titles not returned before	Total for Possible Use
Dec. 29th, 2009					
Springs* AND Restoration AND Conservation	959	3	2	1	1
Springs* AND Restoration AND Hydrogeology	239	2	2	0	0

5) JSTOR

Search	Total	Chosen by Title	Dups	Titles not returned before	Total for Possible Use
Sept 15th, 2009					
Springs* AND restoration AND Prescribed burns**	83	2	0	2	2
Dec. 30th, 2009					
Springs* AND Restoration AND Conservation	2268	2	2	0	0
Jan. 5th, 2010					
Natural Springs AND Restoration AND Conservation	1866	5	0	5	5
Natural Springs OR Riparian Springs OR Catchments AND Restoration	2359	18	7	11	11
Jan. 6th, 2010					
Springs* OR Watershed AND Management AND Hydrology	2798	6	3	3	3
Springs* OR Riparian Springs AND Stabilization AND Geomorphology	116	1	1	0	0
Springs* AND Restoration AND Fencing AND Diversion	11	0	0	0	0
Aug. 13th, 2010					
Arid-land AND Springs AND Riparian AND Restoration	32	1	1	0	0

6) ProQuest-Thesis and Dissertations

Search	Total	Chosen by Title	Dups	Titles not returned before	Total for Use
Jan. 6th, 2010					
Springs* AND Restoration	137	1	0	1	1

Search	Total	Chosen by Title	Dups	Titles not returned before	Total for Use
Springs* AND Conservation	299	0	0	0	0
Springs* AND Management	1621	0	0	0	0
Springs* AND Restoration AND Hydrology	60	1	0	1	1
Springs* AND Restoration AND Stabilization AND Geomorphology	0 – no documents found				
Springs* AND Stabilization AND Geomorphology	0 – no documents found				
Springs* AND Restoration AND Stabilization	0 – no documents found				
Springs* AND Restoration AND Geomorphology	0 – no documents found				
Springs* AND Fencing AND Diversion	1	0	0	0	0
Springs* AND Restoration AND Fencing AND Diversion	1	1	0	0	0
Springs* AND Prescribed Burns[§]	58	1	0	1	1
Springs* AND Restoration AND Prescribed Burns[§]	167	1	1	0	0
Springs* AND Restoration	137	1	1	0	0
Aug. 13th, 2010					
Springs* (OR Riparian Springs OR Natural Springs) AND Arid-land OR Arid land AND Restoration	1	0	0	0	0

7) Academic Search Complete

Search	Total	Chosen by Title	Dups	Titles not returned before	Total for Use
Jan 11th, 2010					
Springs* AND Restoration AND Conservation	102	1	0	1	1
Springs* AND Restoration AND Management	132	1	1	0	0
Springs* AND Watershed AND Restoration AND Management	22	3	1	2	2
Springs* AND Restoration AND Prescribed burns	16	0	0	0	0
Springs* AND Restoration AND Wildfire OR Natural Fire	9	0	0	0	0
Springs* AND Restoration AND Hydrology	24	1	1	0	0
Springs* AND Restoration AND Stabilization AND Geomorphology	1	0	0	0	0

Search	Total	Chosen by Title	Dups	Titles not returned before	Total for Use
Springs* AND Restoration AND Fencing OR Enclosure	1	0	0	0	0
Springs* AND Restoration AND Diversion	6	0	0	0	0
Aug. 13th, 2010					
Springs* AND Arid-land OR Arid land AND Restoration	54 (came back with over 1million titles, so refined to Academic Journals and Invertebrate communities)	1	1	0	0

8) Forest Science Database (Ovid)

Search	Total	Chosen by Title	Dups	Titles not returned before	Total for Use
Sept 15th, 2009					
Springs* AND restoration AND Prescribed burns**	0	0	0	0	0
Jan 11th, 2010					
Springs* (OR Natural Springs) AND Restoration	0	0	0	0	0

9) ISI Web of Science

Search	Total	Chosen by Title	Dups	Titles not returned before	Total for Use
Jan 11th, 2010					
Springs* AND Restoration	70	2	2	0	0
Riparian AND Restoration AND Conservation	244	2	2	1	1
Natural Springs AND Restoration AND Conservation AND Management	6	0	0	0	0
Catchment AND Restoration AND Conservation AND Management	72	1	1	0	0
Watershed AND Restoration AND Conservation AND Management	97	2	1	1	1
Springs AND Restoration AND Prescribed burns	1	0	0	0	0
Springs AND Restoration AND wildfire	0	0	0	0	0
Springs AND Restoration AND natural fire	0	0	0	0	0
Springs AND Restoration AND Enclosure OR Fencing	996	1	1	0	0
Jan 12th, 2010					
Springs AND Restoration AND	2	0	0	0	0

Search	Total	Chosen by Title	Dups	Titles not returned before	Total for Use
Geomorphology					
Springs AND Restoration AND Stabilization	0	0	0	0	0
Springs AND Restoration AND Hydrology	4	0	0	0	0
Aug 13th, 2010 Springs* AND Arid land OR Arid-land AND Restoration AND Monitoring	360	1	1	0	0

10) Google Scholar search

(Restricted search in Biology, Life Sciences, and Environmental Science)

Search	Total	Chosen by Title	Dups	Titles not returned before	Total for Use
Jan 12th, 2010 Springs* (AND Riparian AND Watershed AND Catchment) AND Restoration AND Conservation AND Management	1470	7	1	7	7
Springs* (AND natural springs) AND Restoration AND Hydrology AND Geomorphology AND Stabilization	1030	7	5	2	2
Jan 13th, 2010 Springs* AND Restoration AND Prescribed burns AND Natural fire AND Wildfire	2090 (only displayed first 1000)	6	1	5	5
Springs* AND Restoration AND Diversion AND Fencing AND Enclosure	290	0	0	0	0
Aug 13th, 2010 Springs* AND Arid-land AND Restoration AND Riparian	407	3	3	0	0

11) USDA Forest Service's TreeSearch

Search	Total	Chosen by Title	Dups	Titles not returned before	Total for Use
Jan 13th, 2010					
Springs AND Riparian AND Restoration	1305	0	0	0	0
Springs AND Watershed AND Restoration	1816	0	0	0	0

13) Wilson OmniFile Search

Search	Total	Chosen by Title	Dups	Titles not returned before	Total for Use
Jan 13th, 2010 Springs* AND Restoration AND	97	0	0	0	0

Search	Total	Chosen by Title	Dups	Titles not returned before	Total for Use
Conservation					
Riparian Springs AND Restoration AND Management	3	0	0	0	0
Springs AND Watershed AND Restoration	8	0	0	0	0
Springs AND Catchment AND Restoration	0	-	-	-	-
Natural Springs AND Restoration AND Hydrology	0	-	-	-	-
Springs AND Restoration AND Geomorphology	0	-	-	-	-
Natural Springs AND Restoration AND Stabilization	0	-	-	-	-

12) ERI Electronic Library Search

Search	Total	Chosen by Title	Dups	Titles not returned before	Total for Use
Jan 27th, 2010 Springs* AND Restoration AND Conservation	42	0	0	0	0
Riparian Springs AND Restoration AND Management	26	3	3	0	0
Natural Springs AND Watershed AND Restoration	25	1	1	0	0
Springs AND Catchment AND Restoration	4	1	1	0	0
Springs* AND Restoration AND Prescribed burns[§]	21	1	1	0	0

13) NAU School of Forestry Publication Library

Search	Total	Chosen by Title	Dups	Titles not returned before	Total for Use
Jan 27th, 2010 Springs* AND Restoration AND Conservation AND Management	0	-	-	-	-
Springs* AND Restoration AND Prescribed burns	0	-	-	-	-

14) Arizona Water Protection Fund Online Documents and reports

Search	Total	Chosen by Title	Dups	Titles not returned before	Total for Use
Jan 27th, 2010 No search terms, just looked at what was available	6	6	3	3	3

15) Rocky Mountain Research Station online publications

Search	Total	Chosen by Title	Dups	Titles not returned before	Total for Use
Jan 27th, 2010					
No search terms, just looked at what was available	1	1	0	1	1

Appendix C. Listing of unevaluated studies with IV category Quality of Evidence Classification (Pullin & Knight 2003).

Study Evidence Quality Category	Author(s):	Publication Year:	Restoration Project Name:	Reasoning for Evidence Category Rating:
IV	Natural Channel Design, Inc.	2008	AWPF Grant Projects Evaluation Final Report, Phase II: Case Studies, Case Study: Lynx Creek Restoration at Sediment Trap #2 Grant No: 03-117WPF	This report did not provide details about restoration and monitoring; unable to make full assessment.
IV	Natural Channel Design, Inc.	2008	AWPF Grant Projects Evaluation Final Report, Phase II: Case Studies, Case Study: Riparian and Watershed Enhancement on the A7 Ranch-Lower San Pedro River Grant No.: 99-069WPF	This project assessment report did not provide detail about the initial restoration methods and monitoring; not enough information to determine restoration success.
IV	Natural Channel Design, Inc.	2008	AWPF Grant Projects Evaluation Final Report, Phase II: Case Studies, Case Study: Watershed Improvements to Restore Riparian and Aquatic Habitat at Muleshoe Ranch Grant No.: 97-035WPF	Unable to make full assessment because report was missing information.

Appendix D. Summary of criteria for successful restoration met and left undetermined.

Criteria for successful restoration met

Study	Character-istic Assemblage	Native species present in greatest feasible extent	Functional groups for continued development/ stability	Sustain-able for reproduct-ion	Normal function-ing condition	Integrated into surround-ing landscape	No or limited threats	Resilient to natural disturb-ances	Self-sustain-ing	Number of met criteria	Number of failed criteria	Number of undeter-mined criteria
Anderson et al (2003), Clover Springs	No	No	Yes	Yes	No	Yes	Yes	Yes	Yes	6	3	0
AWPF (2001), Bingham Cienega	Yes	No	Yes	Yes					Yes	4	1	4
Brunson et al (2001), Muleshoe	No	Yes		Yes		Yes	Yes	Yes	No	5	2	2
GCWC (2010) Pakoon Springs Rehabilitation Final Report	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	8	1	0
Katz (2010), San Pedro Riparian Areas	No	No	Yes		No	Yes	Yes	Yes		4	3	2
Kodric-Brown and Brown (2007), Ash Meadows Springs, NV and Dalhousie Spring, Australia		No		No	No				No	0	4	5
Long and Endfield (2000), White Springs				Yes		Yes	Yes	Yes	Yes	5	0	4
Long et al (2004), Soldier Springs			Yes	Yes		Yes	Yes	Yes	Yes	6	0	3

Criteria for successful restoration met

Study	**Character-istic Assemblage**	**Native species present in greatest feasible extent**	**Functional groups for continued development/ stability**	**Sustain-able for reproduct-ion**	**Normal function-ing condition**	**Integrated into surround-ing landscape**	**No or limited threats**	**Resilient to natural disturb-ances**	**Self-sustain-ing**	**Number of met criteria**	**Number of failed criteria**	**Number of undeter-mined criteria**
Muelbauer et al (2008), Fossil Creek	Yes			Yes		Yes	Yes		Yes	5	0	4
Natural Channel Design, Inc (2008), Brown Springs		No			No	No	No			0	4	5
Natural Channel Design, Inc (2008), Clover Springs		No	Yes	Yes		Yes	Yes		Yes	5	1	3
Natural Channel Design, Inc (2008), Hart Prairie		No	Yes	Yes	No	Yes	No			3	3	3
Natural Channel Design, Inc (2008), Hoxworth Springs					Yes	Yes	No	No	No	2	3	4
Springer et al (1999), Hoxworth Springs						Yes	Yes			2	0	7
Weissenfluh (2007), Jackrabbit Springs	No		Yes	Yes		Yes	Yes	No	No	4	3	2

Appendix E. Springs restorations project summaries (*ND indicated no data):

Author(s):	Anderson, Diana, Abe Springer, Jeff Kennedy, Willie Odem, Laura DeWald, and Dick Fleishman					
Restoration Project Name:	Verde River Headwaters Restoration Demonstration Project: Final Report, Arizona Water Protection Fund Grant No.98-059, 2003					
Study Category (Pullin & Knight 2003)	II-2					
Study Objective:	1) Develop and implement a channel stabilization and wetland protection plan for the Clover Springs reach of Forty-four Canyon. 2) Determine the cause of the valley incision and develop an understanding of the local geomorphology in order to contribute to a long-term mitigation plan. 3) Develop outreach and public information products to transfer the results of the demonstration project to the public. 4) Revitalize the wet meadow, and to investigate the long-term geomorphic history of the channel					
Springs Descriptions:	**Name(s)**					
	Clover Springs					
	Type(s):					
	Ephemeral Rheocrene					
	Location(s):					
	Downstream from the State Highway 87 crossing to approx. 0.5 miles downstream, in Forty-four Canyon; NAD83 UTM: N 3818313.75, E 466715.48					
Pre-Intervention Impacts/Disturbances:	**Roads w/in 100 m?**	**Flow diversion or culvert?**	**Alteration to springs source?**	**Agriculture?**	**Grazing?**	**Recreation?**
	Yes	Yes	Yes	No	Yes	Yes
Year Restoration Completed	2003					
Intervention(s) (i.e., Restoration Actions):	1) Removal of existing structures, reshaping and redirecting of the channel, and the use of low impact structures to encourage natural channel stability; 2) The springs protected by maintaining or improving the channel grade; 3) Stream stabilization by construction of sinuous bankfull channel and connection to the original floodplain; 4) Re-vegetation of disturbed uplands and in the newly created channel with the overall objective of revitalizing the plant community of the meadow and to improve surface stability.					
Focused Site Measurements:	1) Spring discharge, 2) high flow, 3) Water temperature, 4) Runoff discharge in Dirtyneck and Fourtyfour Canyons, 5) Channel stability, 6) Percent aerial cover of plant species and abiotic material.					
Target Species:	Plant community of the wet-meadow, i.e., riparian areas and terrestrial areas					
Measured impacts of restoration:	**Hydrology**					
	Geomorphology					
	No to little change along restored longitudinal profiles					
	Invertebrate/Vertebrate Species					
	Vegetation					
	1) Improvement in proportion of riparian and terrestrial species; 2) Not much change in species; 3) Slightly more species in terrestrial plots; 4) Slightly greater grass cover in terrestrial plots; 5) Greater exotic grass and forb species cover than native; 6) More native species than exotic in terrestrial plots compared to riparian; 7) Decrease in popr					
Monitoring duration:	Every four to six weeks for surface water and once every 3 years for channel stability for a total of 4 years					
Post-restoration actions/assessments:	Outreach products include two kiosks at the site, describing the stabilization activities as well as a 25-minute education video available through NAU's Bilby Research Center (ISBN 0-9718786-4-1)					
Objectives Met (yes/no)?	Yes					
Quality Assurance measures:	Yes					
Criteria for successful restoration met (yes/no)?	**Characteristic Assemblage**	**Native species present in greatest feasible extent**	**Functional groups for continued development/ stability of restored ecosystem**	**Sustainable for reproduction**	**Normal functioning condition**	**Integrated**
	No	No	Yes	Yes	No	Yes
	No or limited threats	**Resilient to natural disturbances**	**Self-sustaining**			
	Yes	Yes	Yes			
Total criteria for successful restoration met:	6 - 6/9 = .67 = 67%					
Evaluation of Project	Monitoring does not address long-term changes vegetation. Overall, project was successful in restoring channel stability, but no attention was made to invertebrate species or changes in hydrogeology; Overall score =6/9 = 67% successful based on criteria.					

Author(s):	Arizona Water Protection Fund					
Restoration Project Name:	Bingham Cienega Riparian Restoration Project, Grant No: 97-040WPF					
Study Category (Pullin & Knight 2003)	II-2					
Study Objective:	1) Promote long term re-establishment of deciduous riparian woodland, sacaton grassland and mesquite woodland in abandoned agricultural fields; and 2) Develop practical techniques for promoting establishment of native plants that either does not require irrigation or that require only infrequent irrigation.					
Springs Descriptions:	**Name(s)**					
	Bingham Cienega					
	Type(s):					
	Perennial spring-fed marsh, local aquifer					
	Location(s):					
	Central basin of San Pedro River, between Benson and Pomerence, and San Manuel and Mammoth, AZ, 2000 feet west of lower San Pedro River and 1/4 mile north of Reddington; Township 11 south, Range 18 east, sections 22, 23, 26 and 27.					
Pre-Intervention Impacts/Disturbances:	**Roads w/in 100 m?**	**Flow diversion or culvert?**	**Alteration to springs source?**	**Agriculture?**	**Grazing?**	**Recreation?**
	Yes	Yes	N/A	Yes	Yes	Yes
Year Restoration Completed	2001					
Intervention(s) (i.e., Restoration Actions):	1) Install irrigation system; 2) Re-vegetation – native grasses, trees, and shrubs; 3) Mowed fields and used Round Up to spot spray (mostly Johnson grass) to control exotic species competition; 4) Livestock exclosures with electrical fencing.					
Focused Site Measurements:	1) Ground water depth; 2) precipitation; 3) stream flow; 4) re-vegetation success: presence of flowering, height, and basal diameter; 5) Bird use					
Target Species:	Giant sacaton (Sporobolis wrightii); Sand dropseed (Sporobolis crytandrus); Sideoats gramma (Bouteloua curtipendula); Ash (Frazinus velutina); Walnut (Juglans major); Mesquite (Prosopis velutina); Hackberry (Celtus reticulata)					
Measured impacts of restoration:	**Hydrology**					
	None reported					
	Geomorphology					
	None reported					
	Invertebrate/Vertebrate Species					
	None reported					
	Vegetation					
	High survivorship and flowering frequency of target species in first growing season; Survivorship decreased (average 69.8%) in second growing season					
Monitoring duration:	4 times per year over 3 years					
Post-restoration actions/assessments:	None reported					
Objectives Met (yes/no)?	Yes					
Quality Assurance measures:						
Criteria for successful restoration met (yes/no)?	**Characteristic Assemblage**	**Native species present in greatest feasible extent**	**Functional groups for continued development/ stability of restored ecosystem**	**Sustainable for reproduction**	**Normal functioning condition**	**Integrated**
	Yes	No	Yes	Yes		
	No or limited threats	**Resilient to natural disturbances**	**Self-sustaining**			
			Yes			
Total criteria for successful restoration met:	4					
Evaluation of Project	All criteria could not be determined.					

Author(s):	Brunson, Ed., Dave Gori, and Dana Backer					
Restoration Project Name:	AWPF Project Number 97-035 Watershed improvement to restore riparian and aquatic habitat on the Muleshoe Ranch CMS, Final Report					
Study Category (Pullin & Knight 2003)	II-2					
Study Objective:	1) Conduct prescribed burns to improve watershed condition (2200 acres/year for a total of 6600 acres); change the composition and structure of watershed vegetation by increasing the frequency and cover of perennial grasses, especially mid- to tall-statured species and by decreasing the cover of shrubs. 2) Construct additional perimeter fencing to exclude trespass livestock from Bass Creek and its watershed. 3) Continue to expand ongoing monitoring program for watershed vegetation, riparian vegetation, streamflow, floodplain geomorphology, native fish and aquatic habitat. 4) Post signs at the downstream boundary of Muleshoe CMA in Hot Springs wash to discourage off-road vehicle (ROV) access into lower Hot Springs riparian area. 5) Demonstrate how watershed management techniques can improve both riparian habitats and associated rangeland.					
Springs Descriptions:	**Name(s)**					
	Hot Springs Watershed					
	Type(s):					
	Location(s):					
	Galiuro Mountains, northern Cochise County and southern Graham County, southeastern AZ					
Pre-Intervention Impacts/Disturbances:	**Roads w/in 100 m?**	**Flow diversion or culvert?**	**Alteration to springs source?**	**Agriculture?**	**Grazing?**	**Recreation?**
	Yes				Yes	Yes
Year Restoration Completed	2000					
Intervention(s) (i.e., Restoration Actions):	1) Prescribed burns to upland vegetation through use for aerial ignition; 2) Construct 3 miles of fence on the southeast side of the CMA to keep neighboring livestock from entering upper Bass Canyon riparian area; 3) Install signs at 10 locations where ORV access has been a problem.					
Focused Site Measurements:	Upland and riparian vegetation (canopy cover by species, abundance, stream flow, floodplain and channel geomorphology, aquatic habitat and native fish populations.					
Target Species:	Gila chub (Gila intermedia)					
Measured impacts of restoration:	**Hydrology**					
	No change in water quality. Perennial stream flow decreased due to lack of precipitation.					
	Geomorphology					
	Undercut bank increased					
	Invertebrate/Vertebrate Species					
	Overall increase in chub and native fish populations (captured/year and density); Negative trend in fish density however in Double R, and may have decreased since 1998 or 1999 in Hot Springs and Wildcat Creeks.					
	Vegetation					
	Shrubs: Single burn reduced cover by average of 77% to 83, but surviving shrubs increased immediately; Repeated burns reduced cover 40.8%; Mesquite and snakeweed appears easily killed by fire. ***Grasses and herbs:*** Increase in abundance and cover of annual and perennial grasses and herbs; Double R burn grasses recovered to pre-burn levels one growing season and increased by 25% two growing seasons; annual grasses increased in both average and below average rainfall years. ***Ground cover:*** Total ground cover (little and live basal cover) increased; Litter failed to recover completely in both burns to pre-burn levels after two growing seasons; Basal cover increased after two growing seasons. ***Riparian Forest Structure:*** Target sapling and sapling plus tree densities were met and exceeded by 1998; Adult sapling densities increased. ***Aquatic Habitat:*** Total instream cover, and emergent, floating and overhanging vegetation, riparian tree overstory coverage, and maximum depth of all aquatic macrohabitats increased from 1994 to 1999; woody debris declined; undercut bank increased.					
Number of times monitored:	3 years; where baseflow was monthly and 2 times per year for fence restoration					
Post-restoration actions/assessments:	Continuing monitoring; Plan modified based on results to re-burn units once every 8-10 years to decrease shrubs					
Objectives Met (yes/no)?	Yes					
Quality Assurance measures:	Yes					
Criteria for successful restoration met (yes/no)?	**Characteristic Assemblage**	**Native species present in greatest feasible extent**	**Functional groups for continued development/ stability of restored ecosystem**	**Sustainable for reproduction**	**Normal functioning condition**	**Integrated**
	No	Yes*		Yes		Yes
	No or limited threats	**Resilient to natural disturbances**	**Self-sustaining**			
	Yes	Yes	No**			
Total criteria for successful restoration met:	4					
Evaluation of Project	*In 2000, Chub density and relative (%) abundance increased in the highest numbers and greatest relative abundance since monitoring began. **Not self-sustaining because prescribe burns are recommended to continue to maintain vegetation balance.					

<table>
<tr><th>Author(s):</th><th colspan="6">Grand Canyon Wildlands Council, Inc.</th></tr>
<tr><td>Restoration Project Name:</td><td colspan="6">Pakoon Springs Rehabilitation Final Report</td></tr>
<tr><td>Study Category (Pullin & Knight 2003)</td><td colspan="6">II-2</td></tr>
<tr><td>Study Objective:</td><td colspan="6">1) Create initial hydrologic, soil and vegetation survey; 2) Develop rehabilitation plan; 3) Complete ~10-acre pilot rehabilitation; 4) Monitor rehabilitation progress with rephotography and vegetation surveys; 5) Inform public and partners through volunteer activities, presentations, and site visits.</td></tr>
<tr><td rowspan="6">Springs Descriptions:</td><td colspan="6">Name(s)</td></tr>
<tr><td colspan="6">Pakoon Springs</td></tr>
<tr><td colspan="6">Type(s):</td></tr>
<tr><td colspan="6">Hillslope and Limnocrene</td></tr>
<tr><td colspan="6">Location(s):</td></tr>
<tr><td colspan="6">Mojave Desert, Arizona Strip, Grand Canyon Parashant National Monument</td></tr>
<tr><td rowspan="2">Pre-Intervention Impacts/Disturbances:</td><td>Roads w/in 100 m?</td><td>Flow diversion or culvert?</td><td>Alteration to springs source?</td><td>Agriculture?</td><td>Grazing?</td><td>Recreation?</td></tr>
<tr><td>Yes</td><td>Yes</td><td>Yes</td><td>Yes</td><td>Yes</td><td>Yes</td></tr>
<tr><td>Year Restoration Completed</td><td colspan="6">2010</td></tr>
<tr><td>Intervention(s) (Restoration Actions):</td><td colspan="6">1) Recreate spring mounds/hillside seeps and outflow channels; 2) Removal or reduction of berms constructed from previous owners; 3) Landscape re-shapped around spring sources; 4) Topographic profile recontoured; 5) Non-native plant and animal species eradicated; 6) Areas were revegetated by translocation local native plant stock; 7) Entire area was fenced to exclude feral burros and cattle; 8) Undesired road was removed; 9) Agricultural fields recontoured.</td></tr>
<tr><td>Focused Site Measurements:</td><td colspan="6">Hydrologic: discharge, field water-quality (electrical conductivity, pH, and temp), inorganic lab analyses, and air temp at springs outflow points and Vegetation.</td></tr>
<tr><td>Target Species:</td><td colspan="6"></td></tr>
<tr><td rowspan="8">Measured impacts of restoration:</td><td colspan="6">Hydrology</td></tr>
<tr><td colspan="6"></td></tr>
<tr><td colspan="6">Geomorphology</td></tr>
<tr><td colspan="6">Recontouring eliminated large bullfrog population and buried large cattail stand</td></tr>
<tr><td colspan="6">Invertebrate/Vertebrate Species</td></tr>
<tr><td colspan="6">High avian species richness and densities</td></tr>
<tr><td colspan="6">Vegetation</td></tr>
<tr><td colspan="6">Low mortality, vigorous growth, and natural vegetation recolonization in all areas; natural recolonization of native species</td></tr>
<tr><td>Duration of monitoring:</td><td colspan="6"></td></tr>
<tr><td>Post-restoration actions/assessments:</td><td colspan="6">3 years</td></tr>
<tr><td>Objectives Met (yes/no)?</td><td colspan="6">Yes</td></tr>
<tr><td>Quality Assurance measures:</td><td colspan="6">Yes</td></tr>
<tr><td rowspan="4">Criteria for successful restoration met (yes/no)?</td><td>Characteristic Assemblage</td><td>Native species present in greatest feasible extent</td><td>Functional groups for continued development/ stability of restored ecosystem</td><td>Sustainable for reproduction</td><td>Normal functioning condition</td><td>Integrated</td></tr>
<tr><td>Yes</td><td>No</td><td>Yes</td><td>Yes</td><td>Yes</td><td>Yes</td></tr>
<tr><td>No or limited threats</td><td>Resilient to natural disturbances</td><td>Self-sustaining</td><td></td><td></td><td></td></tr>
<tr><td>Yes</td><td>Yes</td><td>Yes</td><td></td><td></td><td></td></tr>
<tr><td>Total criteria for successful restoration met:</td><td colspan="6">8</td></tr>
<tr><td>Evaluation of Project</td><td colspan="6">Very successful project with included recommendations for continued monitoring and maintenance. Definitely high-quality example.</td></tr>
</table>

Author(s):	Katz, Dr. Gabriell					
Restoration Project Name:	Revised Final Report: Test of Riparian Recovery Following Reduced Groundwater Pumping, Lower San Pedro River, AWPF Grant #08-151WPF					
Study Category (Pullin & Knight 2003)	II-2					
Study Objective:	Overall: Test the effectiveness of a hydrologic-based approach to riparian ecosystem restoration on the lower San Pedro River through, 1) Document trends in controlling variables; 2) Document short-term indicators of riparian ecosystem change; 3) Document long-term indicators of riparian ecosystem change; and 4) Assess patterns of change and vegetation-hydrology relationships. Restoration target was not defined as a return to pre-entrenchment conditions, but as attainment of wetter conditions on the post-entrenchment river and floodplain.					
Springs Descriptions:	**Name(s)**					
	Type(s):					
	Location(s):					
	San Pedro River, Sonora, Mexico to Gila River, Winkelman, AZ					
Pre-Intervention Impacts/Disturbances:	**Roads w/in 100 m?**	**Flow diversion or culvert?**	**Alteration to springs source?**	**Agriculture?**	**Grazing?**	**Recreation?**
				Yes	Yes	Yes
Year Restoration Completed	2007					
Intervention(s) (Restoration Actions):	Reduced pumping rates to negligible levels					
Focused Site Measurements:	Vegetation and water table level					
Target Species:						
Measured impacts of restoration:	**Hydrology**					
	Geomorphology					
	Invertebrate/Vertebrate Species					
	Vegetation					
	Perennial-flow reference sites had higher herbaceous cover, higher species richness, lower weighted wetland indicator scores, and higher relative cover of hydric perennials and hydric annuals than non-perennial sites; non-perennial sites had higher relative cover of mesic perennials and xeric annuals; average relative cover of non-native species was high, on the order of 70%, and did not differ between perennial and non-perennial reference sites; increased floodplain proportion of forest and woodland, and increased basal area of cottonwood and willow; declines in total floodplain woody stem density, basal area, and vegetation volume were generally more pronounced at reference sites than at restoration sites.					
Duration of monitoring:	7 years					
Post-restoration actions/assessments:	Continued monitoring is needed to determine whether hydric annuals will be replaced by hydric perennials at H&E Farm in response to the shift towards more permanent water availability.					
Objectives Met (yes/no)?	Yes					
Quality Assurance measures:						
Criteria for successful restoration met (yes/no)?	**Characteristic Assemblage**	**Native species present in greatest feasible extent**	**Functional groups for continued development/ stability of restored ecosystem**	**Sustainable for reproduction**	**Normal functioning condition**	**Integrated**
	No	No	Yes		No	Yes
	No or limited threats	**Resilient to natural disturbances**	**Self-sustaining**			
	Yes	Yes				
Total criteria for successful restoration met:	4					
Evaluation of Project	Project data indicate that restoration goals for the streamside herbaceous community have largely been achieved at Three Links Farm, but not at H&E Farm.					

Author(s):	Kodric-Brown, Astrid, and James H Brown					
Restoration Project Name:	Native fishes, exotic mammals, and the conservation of desert springs					
Study Category (Pullin & Knight 2003)	II-3					
Study Objective:	Document the history and current conservation status of spring systems in some detail and then draw some general lessons for the conservation and management of desert spring ecosystems.					
Springs Descriptions:	**Name(s)**					
	Ash Meadows Springs (AMS) = Devils Hole Spring, School Spring, and Mexican Spring; Dalhousie Springs (DHS)					
	Type(s):					
	Location(s):					
	Amargosa River basin of western Nevada, USA; Northern South Australia					
Pre-Intervention Impacts/Disturbances:	**Roads w/in 100 m?**	**Flow diversion or culvert?**	**Alteration to springs source?**	**Agriculture?**	**Grazing?**	**Recreation?**
	Yes	Yes	Yes	Yes	Yes	Yes
Year Restoration Completed	AMS: 1984; DHS: 1995					
Intervention(s) (i.e., Restoration Actions):	**Ash Meadows:** 1) Fencing of entire area to exclude all feral and domestic livestock; 2) Removal of exotic plant and animal species. **Dalhousie:** 1) Removal of feral livestock; 2) Fence major springs; 3) Removal of exotic plant and animal species; 4) Limit tourist traffic.					
Focused Site Measurements:	1) Aquatic and riparian vegetation production; 2) Native fish species.					
Target Species:	AMS: Pupfish and Amargosa toad (Bufo nelsoni).					
Measured impacts of restoration:	**Hydrology**					
	Ash Meadows: Reduction in open-water habitat and fish populations. ***Dalhousie:*** 1) Source pools and out-flows heavily overgrown; 2) Anoxic water due to large quantities of dead and decomposing vegetation; 3) Open-water only in source pools and major outflows of largest springs.					
	Geomorphology					
	Ash Meadows: Reduction in open-water habitat and fish populations. ***Dalhousie:*** Open-water only in source pools and major outflows of largest springs.					
	Invertebrate/Vertebrate Species					
	Dalhousie: In the largest springs, fish assemblages exhibited a near-perfect nested subset structure with five species; 18 extinctions and two colonization's recorded in 2003-majority of extinctions in small springs.					
	Vegetation					
	Ash Meadows: Increase in aquatic and riparian vegetation ***Dalhousie:*** 1) Source pools and out-flows heavily overgrown; 2) Anoxic water due to large quantities of dead and decomposing vegetation.					
Monitoring duration:	AMS: On-going; DHS: one time surveys on 1991 and 2003					
Post-restoration actions/assessments:	AMS: Desire to remove emergent plants and preserve open water					
Objectives Met (yes/no)?	Kodric-Brown and Borwn's study objectives were met. Objectives of restoration projects not known.					
Quality Assurance measures:	No					
Criteria for successful restoration met (yes/no)?	**Characteristic Assemblage**	**Native species present in greatest feasible extent**	**Functional groups for continued development/ stability of restored ecosystem**	**Sustainable for reproduction**	**Normal functioning condition**	**Integrated**
		No		No	No	
	No or limited threats	**Resilient to natural disturbances**	**Self-sustaining**			
			No			
Total criteria for successful restoration met:	0					
Evaluation of Project	This report was an evaluation on the restoration of these sites by a third party. Total exclusion of livestock appears to have led to the demise of these restorations. However, restoration has continued at Ash Meadows since this publication. Was only able to determine 4 out of 9 criteria.					

Author(s):	Long, Jonathan W., B. Mae Burnette, Alvin L. Medina, and Joshua L. Parker					
Restoration Project Name:	Restoration of Soldier Spring: and isolated habitat for native Apache trout					
Study Category (Pullin & Knight 2003)	II-2					
Study Objective:	Repair degradated channels through reforming riffle features					
Springs Descriptions:	**Name(s)**					
	Soldier Spring					
	Type(s):					
	Hillslope					
	Location(s):					
	White Mountain Apache Reservation, eastern Arizona					
Pre-Intervention Impacts/Disturbances:	**Roads w/in 100 m?**	**Flow diversion or culvert?**	**Alteration to springs source?**	**Agriculture?**	**Grazing?**	**Recreation?**
					Yes	
Year Restoration Completed	2000					
Intervention(s) (Restoration Actions):	Fencing exclosures, sedge transplanting , placement of rock riffle formations					
Focused Site Measurements:						
Target Species:	Apache trout (Oncorhynchus apache)					
Measured impacts of restoration:	**Hydrology**					
	Geomorphology					
	Channel bed refilled, water depth and width increased, percent fine gravels doubled and size class represents preferred substrate for Apache trout; long pools maintained above riffle formations and short pools below.					
	Invertebrate/Vertebrate Species					
	Trout abundance rebounded					
	Vegetation					
	Streamside vegetation growth vigorous, with transplanted sedges bounding to streambed and climbing higher along banks; riffle structures interwoven with aquatic veg including butterbup (Ranunculus aquatilis), mannagrass (Glyceria spp.), and sedges (Carex spp.); flow concentrated by aquatic plants making gravel substrates					
Duration of monitoring:	4 years					
Post-restoration actions/assessments:	Deepening pools could improve conditions for trout; Fish surveying methods were different in 2002					
Objectives Met (yes/no)?	Yes					
Quality Assurance measures:						
Criteria for successful restoration met (yes/no)?	**Characteristic Assemblage**	**Native species present in greatest feasible extent**	**Functional groups for continued development/ stability**	**Sustainable for reproduction**	**Normal functioning condition**	**Integrated**
			Yes	Yes		Yes
	No or limited threats	**Resilient to natural disturbances**	**Self-sustaining**			
	Yes	Yes	Yes			
Total criteria for successful restoration met:	6					
Evaluation of Project	Restoration met 6 out of 9 criteria for successful restoration and also met it's originally stated objectives. Three out of the 9 criteria could not be determined.					

Author(s):	Long, Jonathan W. and Delbin Endfield					
Restoration Project Name:	Restoration of White Springs					
Study Category (Pullin & Knight 2003)	III					
Study Objective:	Restore a culturally and ecologically important spring that had been damaged in the aftermath of a wildfire					
Springs Descriptions:	**Name(s)**					
	White Springs					
	Type(s):					
	Limnocrene or rheocrene					
	Location(s):					
	Cibecue Canyon, White Mountain Apache Reservation					
Pre-Intervention Impacts/Disturbances:	**Roads w/in 100 m?**	**Flow diversion or culvert?**	**Alteration to springs source?**	**Agriculture?**	**Grazing?**	**Recreation?**
	Yes	No	Yes	No	Yes	Yes
Year Restoration Completed	2000					
Intervention(s) (Restoration Actions):	Rock structures, road closures, fencing and revegetation					
Focused Site Measurements:						
Target Species:						
Measured impacts of restoration:	**Hydrology**					
	Water quality improved - based from visual observation					
	Geomorphology					
	Channel stabilized and downcutting was reversed; rocks and litter fill the rock structures; pools and riffles reformed upstream of rock structures					
	Invertebrate/Vertebrate Species					
	Vegetation					
	Spring area became lush with plants including watercress, yellow monkey flower (Mimulus guttatus) and various grasses.					
Duration of monitoring:						
Post-restoration actions/assessments:	Continued restoration required upstream until watershed conditions stabilize					
Objectives Met (yes/no)?	Yes					
Quality Assurance measures:						
Criteria for successful restoration met (yes/no)?	**Characteristic Assemblage**	**Native species present in greatest feasible extent**	**Functional groups for continued development/stability of restored ecosystem**	**Sustainable for reproduction**	**Normal functioning condition**	**Integrated**
				Yes		Yes
	No or limited threats	**Resilient to natural disturbances**	**Self-sustaining**			
	Yes	Yes	Yes			
Total criteria for successful restoration met:	5					
Evaluation of Project	Overall successful project however continued restoration is recommended on riffle structures. Was not able to determine four of the nine criteria for successful restoration.					

Author(s):	Muehlbauer, Jeffrey D., Carri J LeRoy, Jacqueline M Lovett, Kathleen K Flaccus, Julie K Vlieg, and Jane C Marks					
Restoration Project Name:	Short-term responses of decomposers to flow restoration in Fossil Creek, Arizona, USA					
Study Category (Pullin & Knight 2003)	II-2					
Study Objective:	To quantify some short-term effects of returning full flow below the Fossil Creek Dam					
Springs Descriptions:	**Name(s)**					
	Fossil Springs/Fossil Creek					
	Type(s):					
	Rheocrene					
	Location(s):					
	West of Strawberry, AZ. Lat 342524.10 Long 1113426.52					
Pre-Intervention Impacts/Disturbances:	**Roads w/in 100 m?**	**Flow diversion or culvert?**	**Alteration to springs source?**	**Agriculture?**	**Grazing?**	**Recreation?**
	No	Yes	No	No	No	Yes
Year Restoration Completed	2005					
Intervention(s) (Restoration Actions):	Dam decommissioned					
Focused Site Measurements:	Leaf litter decomposition, Macroinvertebrate community attributes fungal biomass, and water quality and chemistry.					
Target Species:	Populus fremontii and Alnus oblongifolia leaves					
Measured impacts of restoration:	**Hydrology**					
	1) Water below the dam warmed by 9°C, from 11.6°C in 2003 to 20.6°C in 2005; 2) TdS and SpC concentrations below the dam in 2005 increased relative to their concentrations in 2003 and in proportion to the above-dam values; 3) pH above and below the dam in 2005 both decreased relative to 2003 values, and pH remained lower above in comparison to below the dam.					
	Geomorphology					
	"Below-dam" monitoring site was shallower and narrower before flow restoration					
	Invertebrate/Vertebrate Species					
	1) Below-dam macroinvertebrate community began to resemble the above-dam species structure- Macroinvertebrate assemblages on litterbags exhibited a greater degree of homogeneity and had similar diversity; 2) Ordination of macroinvertebrates collected below the dam was still more dispersed than the above-dam community.					
	Vegetation					
	Fungal biomass at the two sites was nearly equal, and both values were approximately 30% greater than the average fungal biomass on leaves located above the dam in 2003					
Monitoring duration:	18 months in 2003 and 6 months in 2005					
Post-restoration actions/assessments:						
Objectives Met (yes/no)?	Yes					
Quality Assurance measures:						
Criteria for successful restoration met (yes/no)?	**Characteristic Assemblage**	**Native species present in greatest feasible extent**	**Functional groups for continued development/ stability of restored ecosystem**	**Sustainable for reproduction**	**Normal functioning condition**	**Integrated**
	Yes			Yes		Yes
	No or limited threats	**Resilient to natural disturbances**	**Self-sustaining**			
	Yes		Yes			
Total criteria for successful restoration met:	5					
Evaluation of Project	This article does not directly report on the restoration efforts; However, these researchers conclude that the restoration was successful. Could determine 5 out of the 9 criteria as successful; the other 4 could not determine. From the criteria that could be determined, this restoration was 56% successful. This article was considered because it is a spring-fed stream.					

Author(s):	Natural Channel Design, Inc.					
Restoration Project Name:	AWPF Grant Projects Evaluation Final Report, Phase II: Case Studies, Case Study: Hoxworth Springs Riparian Restoration, Grant No: 96-003WPF					
Study Category (Pullin & Knight 2003)	III					
Study Objective:	1) Reduce accelerated streambank erosion and soil movement out of the riparian area and to re-establish adequate vegetative characteristics to provide channel stability; 2) Monitor changes in the riparian vegetation associated with the restoration of the perennial stream; 3) Quantify the amount of spring discharge and surface runoff in the proposed restoration area.					
Springs Descriptions:	**Name(s)**					
	Hoxworth Springs					
	Type(s):					
	Rheocrene					
	Location(s):					
	Lake Mary watershed, Coconino National Forest, ~15 miles south of Flagstaff, AZ; Lat 35022495 Long 111342954					
Pre-Intervention Impacts/Disturbances:	**Roads w/in 100 m?**	**Flow diversion or culvert?**	**Alteration to springs source?**	**Agriculture?**	**Grazing?**	**Recreation?**
		Yes				
Year Restoration Completed	ND					
Intervention(s) (i.e., Restoration Actions):	Re-shaped the channel to increase meanders and create banks with 3:1 slope that is connected to floodplain; Seeding and riparian plantings growth.					
Focused Site Measurements:	None reported					
Target Species:	None reported					
Measured impacts of restoration:	**Hydrology**					
	Functioning hydrological conditions.					
	Geomorphology					
	Re-shaped the channels are a stable with functioning hydrological conditions.					
	Invertebrate/Vertebrate Species					
	ND					
	Vegetation					
	Seeding and riparian plantings growth					
Monitoring duration:	Not reported					
Post-restoration actions/assessments:	The project objectives were successfully completed.					
Objectives Met (yes/no)?	Yes					
Quality Assurance measures:	None reported					
Criteria for successful restoration met (yes/no)?	**Characteristic Assemblage**	**Native species present in greatest feasible extent**	**Functional groups for continued development/ stability of restored ecosystem**	**Sustainable for reproduction**	**Normal functioning condition**	**Integrated**
					Yes	Yes
	No or limited threats	**Resilient to natural disturbances**	**Self-sustaining**			
	No	No	No			
Total criteria for successful restoration met:	2					
Evaluation of Project	Initial objectives met, but exclosure was removed and some items are starting to fail. Could be said that the project was initially successful. No reporting on many categories for the criteria for successful restoration, therefore unable to make solid analysis of success. From the criteria reported, this project only met 2 out of 9 of the criteria = 22% successful. However, only 5 out of 9 criteria could be determined. Therefore, from 5, 2 out of 5 were met = 67% successful.					

Author(s):	Natural Channel Design, Inc.					
Restoration Project Name:	AWPF Grant Projects Evaluation Final Report, Phase II: Case Studies, Case Study: Watershed Restoration on a High-Elevation Riparian Community, Grant No: 98-050WPF					
Study Category (Pullin & Knight 2003)	III					
Study Objective:	1) Modify watershed conditions to increase and sustain water flows into the riparian community through prescribed burning and reducing the density of pines encroaching the wet meadow toward the riparian community; 2) Reduce/eliminate stock tanks and an artificial dam in the watershed followed by stream channel restoration; 3) Continue and expand the ongoing monitoring of watershed and riparian vegetation, stream flow, and fluvial geomorphology; 4) Fence to control grazing of large ungulates to expedite recovery of vegetation composition and quality and surface hydrology; 5) Conduct public outreach activities on the concepts of watershed and riparian restoration in order to improve public awareness and support for these types of riparian restoration activities.					
Springs Descriptions:	**Name(s)**					
	Hart Prairie springs					
	Type(s):					
	Seeps					
	Location(s):					
	Hart Prairie; Coconino National Forest, Forest Service Road 151, 13 miles north of Flagstaff, AZ, near Nature Conservancy					
Pre-Intervention Impacts/Disturbances:	**Roads w/in 100 m?**	**Flow diversion or culvert?**	**Alteration to springs source?**	**Agriculture?**	**Grazing?**	**Recreation?**
	Yes	Yes	No	No	Yes	Yes
Year Restoration Completed						
Intervention(s) (i.e., Restoration Actions):	1) Remove stock tanks; 2) Fence sensitive areas with elk exclosures; 3) Thin Ponderosa Pine trees by prescribed fires; 4) Remove diversion structures.					
Focused Site Measurements:	1) Water quality; 2) understory percent cover; 3) Bebb Willow regeneration					
Target Species:	Bebb Willow, Sedges and rushes					
Measured impacts of restoration:	**Hydrology**					
	Increased flow and riparian water quantities increased					
	Geomorphology					
	Flow reconnected to stream from removal of unnamed tank; channel stabilizing					
	Invertebrate/Vertebrate Species					
	Vegetation					
	Elk exclosure beneficial in maintaining vegetation; vegetation covering old headcuts to stream are contributing to channel stabilization; vegetation rebounding.					
Monitoring duration:	Monthly (plus 14 years of independent, unfunded monitoring)					
Post-restoration actions/assessments:	Continued work, projects, monitoring, and maintenance contribute immensely to the success of this project.					
Objectives Met (yes/no)?	Yes					
Quality Assurance measures:	None reported					
Criteria for successful restoration met (yes/no)?	**Characteristic Assemblage**	**Native species present in greatest feasible extent**	**Functional groups for continued development/ stability of restored ecosystem**	**Sustainable for reproduction**	**Normal functioning condition**	**Integrated**
		No	Yes	Yes	No	Yes
	No or limited threats	**Resilient to natural disturbances**	**Self-sustaining**			
	No					
Total criteria for successful restoration met:	3					
Evaluation of Project	Unable to make full analysis of success; details about criteria for successful restoration is lacking. From what was reported, this project scored 3 out of 9 = 33% success. However, this does not adequately represent the project's success. If evaluated from the criteria that were reported, project was 50% successful. Objectives of the project were met, so that is a success in its own.					

Author(s):	Natural Channel Design, Inc.					
Restoration Project Name:	AWPF Grant Projects Evaluation Final Report, Phase II: Case Studies, Case Study: Verde River Headwaters Riparian Restoration Project Grant No.: 98-059WPF					
Study Category (Pullin & Knight 2003)	III					
Study Objective:	1) Develop and implement channel stabilization and wetland protection plan for Clover Springs/Clover Creek; 2) Protect rare upland riparian wetland meadow, stabilize degrading stream channel, and control downstream headcuts; 3) Protect springs, improve moisture storage, vegetation, and habitat; 4) Gain knowledge to apply to other headcut sites; 5) Determine causes and timing of reach incision to develop long-term restoration strategy; 6) Educate public about ecosystem, disturbance, and restoration.					
Springs Descriptions:	**Name(s)**					
	Clover Springs					
	Type(s):					
	Ephemeral Rheocrene					
	Location(s):					
	Downstream from the State Highway 87 crossing to approx. 0.5 miles downstream, in Forty-four Canyon; NAD83 UTM: N 3818313.75, E 466715.48					
Pre-Intervention Impacts/Disturbances:	**Roads w/in 100 m?**	**Flow diversion or culvert?**	**Alteration to springs source?**	**Agriculture?**	**Grazing?**	**Recreation?**
	Yes	Yes	Yes	No	Yes	Yes
Year Restoration Completed						
Intervention(s) (i.e., Restoration Actions):	1) Fabric seeding; 2) Bank stabilization: bank reshaping on right (5:1) and left bank (3:1); 3) Grade stabilization: large rock drop (~5 feet) structure (cross-vane weir); 4) Channel modification: existing channel filled and meander increased where possible & road closure.					
Focused Site Measurements:	Vegetation and channel stability					
Target Species:	Plant community of the wet-meadow, i.e., riparian areas and terrestrial areas					
Measured impacts of restoration:	**Hydrology**					
	Geomorphology					
	Invertebrate/Vertebrate Species					
	Vegetation					
	1) Some species of rushes are harder to establish than others; 2) Hydro-mulching and/or fabric for seed establishment worked well; 3) Elk exclosure has protected meadow and allowed vegetation to become vigorous; 4) Sedges and rushes recruitment high.					
Monitoring duration:	Not reported					
Post-restoration actions/assessments:	Vegetation of old road is not as robust as it could be, possibly from compaction over the years.					
Objectives Met (yes/no)?	Yes					
Quality Assurance measures:	Not reported					
Criteria for successful restoration met (yes/no)?	**Characteristic Assemblage**	**Native species present in greatest feasible extent**	**Functional groups for continued development/ stability of restored ecosystem**	**Sustainable for reproduction**	**Normal functioning condition**	**Integrated**
		No	Yes	Yes		Yes
	No or limited threats	**Resilient to natural disturbances**	**Self-sustaining**			
	Yes		Yes			
Total criteria for successful restoration met:	5					
Evaluation of Project	This project assessment report did not provide detail about the initial restoration methods and monitoring. Project objectives were stated as met in the report, therefore successful in that sense. Scored 5 out of 9 = 56% successful; However, unable to assign scores to 3 out of 9 criteria.					

Author(s):	Natural Channel Design, Inc.					
Restoration Project Name:	AWPF Grant Projects Evaluation Final Report, Phase II: Case Studies, Case Study: Brown Creek Riparian Restoration Grant No: 99-095WPF					
Study Category (Pullin & Knight 2003)	III					
Study Objective:	1) Improve riparian and aquatic habitat at Brown Spring and along Brown Creek by excluding livestock grazing in the area 2) Implement a monitoring program to measure the improvements of vegetative cover and stream bank stabilization along Brown Creed riparian corridor.					
Springs Descriptions:	**Name(s)**					
	Brown Spring					
	Type(s):					
	Location(s):					
	Lakeside Ranger District, Fort Apache Reservation, Lat 34025515 Long 109411536					
Pre-Intervention Impacts/Disturbances:	**Roads w/in 100 m?**	**Flow diversion or culvert?**	**Alteration to springs source?**	**Agriculture?**	**Grazing?**	**Recreation?**
	Yes				Yes	Yes
Year Restoration Completed	Not reported					
Intervention(s) (Restoration Actions):	1) Livestock exclosure; 2) Manage native riparian and aquatic communities					
Focused Site Measurements:						
Target Species:						
Measured impacts of restoration:	**Hydrology**					
	Geomorphology					
	Invertebrate/Vertebrate Species					
	Vegetation					
	Exclosure effective in inhibiting use which allows for riparian corridor to heal					
Monitoring duration:	Not reported					
Post-restoration actions/assessments:	1) Buck and pole fencing is not very effective, does not hold up well; 2) Not enough OHV restrictions, signage is not enough; 3) Native riparian vegetation planting would have been useful in replenishing the area; 4) Seeding uplands while grazing is taking place is ineffective; 5) Relocation of unofficial campsite may be useful to limit OHV use.					
Objectives Met (yes/no)?	No					
Quality Assurance measures:	Not reported					
Criteria for successful restoration met (yes/no)?	**Characteristic Assemblage**	**Native species present in greatest feasible extent**	**Functional groups for continued development/ stability of restored ecosystem**	**Sustainable for reproduction**	**Normal functioning condition**	**Integrated**
		No			No	No
	No or limited threats	**Resilient to natural disturbances**	**Self-sustaining**			
	No					
Total criteria for successful restoration met:	0					
Evaluation of Project	Project was very limited in its success. Initial success what that the exclosure was effective in enabling the riparian corridor to heal. However, many interventions were not successful and grazing continues to degrade vegetation. Recreation also dampers the effectiveness of restoration actions. Much more would have to be implemented to promote a successful restoration.					

Author(s):	Springer, Abe, Tim Godwin, Laura DeWald, and Jeff Hink					
Restoration Project Name:	Final Project Progress Report Arizona Water Protection Fun Grant No:96-0003WPF					
Study Category (Pullin & Knight 2003)	II-1					
Study Objective:	Restore pre-disturbance channel morphology and riparian ecosystem of channelized portion of a perennial stream that is supplied water from Hoxworth Springs.					
Springs Descriptions:	**Name(s)**					
	Hoxworth Springs					
	Type(s):					
	Rheocrene					
	Location(s):					
	Mogollon Rim of SW Colorado Plateau, approx. 16 km southeast of Flagstaff, AZ. Lat 350225, Lon 1113427					
Pre-Intervention Impacts/Disturbances:	**Roads w/in 100 m?**	**Flow diversion or culvert?**	**Alteration to springs source?**	**Agriculture?**	**Grazing?**	**Recreation?**
	Yes	Yes	No	No	Yes	Yes
Year Restoration Completed	1999					
Intervention(s) (Restoration Actions):	1) Channel banks reshaped increasing depth to width ratio; 2) Log structures placed in channel banks and reinforced with steel posts; 3) Head-cut drop structures constructed with local basalt and limestone, reinforced with concrete; 4) Channel stabilized below and above head-cut drop structures with local bedrock; 5) Erosion control netting and re-seeding with native grass over disturbed areas; 6) Vegetation plugs transplanted in exposed soil areas in April 1999 and re-seeded in late June/July 1999; 7) Plugs and bare soil were covered with straw and wire fencing to deter grazing; 8) Vegetation transects in restored and grazing exclosure for monitoring including photopoints, with 27 permanent transects representing different degrees of exclosure to grazing.					
Focused Site Measurements:	Spring discharge, runoff, and water level and vegetation					
Target Species:						
Measured impacts of restoration:	**Hydrology**					
	Geomorphology					
	Invertebrate/Vertebrate Species					
	Vegetation					
	Total exclosure overall: More litter, bentgrass (native), less black medick (introduced forb), and slightly less Kentucky bluegrass (introduced, most common). ***Upland, total exclosure:*** less bare ground, more wester wheatgrass and Arizona fescuew (native), same amount blue gramma (native) and Kentucky bluegrass (dominant). ***Riparian, total exclosure:*** More litter, more spike-rush (introduced), less Kentucky bluegrass and Juncus ensifolius (native rush). ***Cattle exclosure (elk grazing only):*** Less litter, more rock and water, much less Kentucky bluegrass, more black medick and bentgrass, and mixed area with Kentucky bluegrass, black medick, blue grammea, meadow fescue, and bentgrass. ***Upland, cattle ex only:*** less litter and slightly less bare ground, much less rattlesnake weed, less Kent. bg, more black medick, and dominated by blue gramma. ***Riparian, cattle ex only:*** Less bare ground and litter, less Kent. bg. more black medick and Cares spp., meadow fescue dominates. ***No exclosure, total grazing*:** Less bare ground and litter, more water, less rattlesnake weed and Kent. bg., more western wheatgrass and black medick and mixed Feel, Melu Bogr, and Agsm rather than Kent. bg. dominated. ***Upland, total grazing:*** More bare ground, less rattlesnake weed, more western wheatgrass and black medic, and ~equal mix of Kentucky bg and western wheatgrass, with more blue gramma and black medick. ***Riparian, total grazing:*** Less bare ground, less Kent. bg., more meadow fescue and western wheatgrass.					
Duration of monitoring:	1 year					
Post-restoration actions/assessments:	The aquifer was more saturated related to high snowmelt and caused peak spring discharge. Spring discharge is relatively constant except during large snowmelts. Runoff that is beyond perennial reach usually only occurs for a few weeks and is intermittent. There is no significant variation in water quality, except for temperature dependent reactions.					
Objectives Met (yes/no)?	Yes					
Quality Assurance measures:						
Criteria for successful restoration met (yes/no)?	**Characteristic Assemblage**	**Native species present in greatest feasible extent**	**Functional groups for continued development/stability of restored ecosystem**	**Sustainable for reproduction**	**Normal functioning condition**	**Integrated**
						Yes
	No or limited threats	**Resilient to natural disturbances**	**Self-sustaining**			
	Yes					
Total criteria for successful restoration met:	2					
Evaluation of Project	Project didn't address many of the criteria for successful restoration. Overall, the restoration was successful in that the project met its original stated objectives. It is important to note though that the missing criteria couldn't be evaluated					

Author(s):	Springer, Abe, Tim Godwin, Laura DeWald, and Jeff Hink
	because that information was not available.

Author(s):	Weissenfluh, Darrick (prepared by), Quantell, Inc. (compiled)					
Restoration Project Name:	The Upper Jackrabbit Restoration (Phase 1) Site, A Step-by-Step Report, Ash Meadows National Wildlife Refuge, Nye County, Nevada					
Study Category (Pullin & Knight 2003)	III					
Study Objective:	1) Utilize integrated management activities to improve lands unlikely to recover naturally from severe wildland fire damage by emulating historic ecosystem structure, function, diversity, and dynamics according to approved land management plans; 2) Restore or establish healthy, functioning ecosystems, even if these ecosystems cannot fully emulate historic or pre-fire conditions as specified in approved land management plans; 3) Control monotypic salt cedar (Tamarix ramosissima), Russian knapweed (Acroptilon repens), common reed (Phragmites australis) and southern cattail (Typha domingensis) to approved land management plan standards.					
Springs Descriptions:	**Name(s)**					
	Jackrabbit spring					
	Type(s):					
	Rheocrene					
	Location(s):					
	Ash Meadows National Wildlife Refuge, Amargosa Valley, Nye County					
Pre-Intervention Impacts/Disturbances:	**Roads w/in 100 m?**	**Flow diversion or culvert?**	**Alteration to springs source?**	**Agriculture?**	**Grazing?**	**Recreation?**
	Yes	No	No	No	No	No
Year Restoration Completed	2006					
Intervention(s) (Restoration Actions):	1) Modification of stream channels and deep water marshes, which will significantly decrease invasive species establishment; 2) Control non-native invasive species populations to establish healthy, functioning ecosystems as outlined in approved land management plans; 3) Adaptive planting of native species in disturbed areas to prevent the re-establishment of non-native invasive species and stabilize the soil.					
Focused Site Measurements:	1) Native plants for health and prosperity (visually); 2) Detection/control of the non-native invasive plants; 3) Native fish populations, and non-native invasive aquatic species.					
Target Species:	1) Ash Meadows Amargosa pupfish (Cyprinidon nevadensis mionectes); 2) Ash Meadows speckled dace (Rhinichthys osculus nevadensis); 3) Ash Meadows milkvetch (Astragalus phoenix); 4) spring-loving centaury (Centaurium namophilum); 5) Ash Meadows gumplant (Grindelia fraxino-pratensis); 6) Ash Meadows ivesia (Ivesia eremica).					
Measured impacts of restoration:	**Hydrology**					
	Geomorphology					
	Rechannelized					
	Invertebrate/Vertebrate Species					
	Increased Ash Meadows Amargosa pupfish downstream after rechannelization					
	Vegetation					
	1) Princess plume (Stanleya pinnata) and inland saltgrass (Distichlis spicata) earliest successional species upland. Both are desirable natives; 2) 65% success from replantings; 3) Mesquite germination from used mesquite woodchips.					
Duration of monitoring:	On-going					
Post-restoration actions/assessments:	1) Non-native/invasive plant species are removed when detected; 2) Effective monitoring plan is being devised.					
Objectives Met (yes/no)?	Yes					
Quality Assurance measures:	None reported					
Criteria for successful restoration met (yes/no)?	**Characteristic Assemblage**	**Native species present in greatest feasible extent**	**Functional groups for continued development/ stability of restored ecosystem**	**Sustainable for reproduction**	**Normal functioning condition**	**Integrated**
	No*		Yes	Yes		Yes
	No or limited threats	**Resilient to natural disturbances**	**Self-sustaining**			
	Yes	No	No**			
Total criteria for successful restoration met:	4					
Evaluation of Project	*Non-native and invasive *Drip irrigation system is being used, and recommended to continue monitoring to determine future maintenance.					

Appendix F. Reference list providing full citations of all included studies:

Anderson, D., Springer, A., Kennedy, J., Odem, W., DeWald, L., Fleishman, D., 2003.Verde River Headwaters Restoration Demonstration Project: Final Report, Arizona Department of Water Resources Water Protection Fund, Grant No. 98-059.

Arizona Water Protection Fund, 2001. Bingham Cienega Riparian Restoration Project, Final Report, Grant # 97-040WPF, Pima County, AZ.

Brunson, E., Gori, D., Backer, D., 2001. Watershed improvement to restore riparian and aquatic habitat on the Muleshoe Ranch CMS, Final Report, The Nature Conservancy, AWPF Project Number 97-035.

Grand Canyon Wildlands Council, Inc., 2010. Pakoon Springs Rehabilitation, Final Report, Task #9, AWPF Grant Contract #06-137WPF, Flagstaff, AZ.

Katz, G., 2010. Revised Final Report: Test of Riparian Recovery Following Reduced Groundwater Pumping, Lower San Pedro River, AWPF Grant #08-151WPF, Appalachian State University, Boone, NC.

Kodric-Brown, A., Brown, J.H., 2007. Native fishes, exotic mammals, and the conservation of desert springs, Frontiers in Ecology 5(10), 549-553.

Long, J.W., Burnette, B.M., Medina, A.L., Parker, J.L., 2004. Restoration of Soldier Spring: and isolated habitat for native Apache trout. In Proceedings, International Conference, 16th, Victoria, Canada, Society for Ecological Restoration, 1-5.

Long, J.W., Endfield, D., 2000. Restoration of White Spring. In Proceedings, USDA Forest Service Rocky Mountain Research Station-P-13, 359-360.

Muehlbauer, J.D., LeRoy, C.J., Lovett, J.M., Flaccus, K.K., Vlieg, J.K., Marks, J.C., 2009. Short-term responses of decomposers to flow restoration in Fossil Creek, Arizona, USA. Hydrobiologia 618, 35–45.

Natural Channel Design, Inc., 2008. AWPF Grant Projects Evaluation, Phase II: Case Studies, Final Report. Arizona Water Protection Fund, Phoenix, AZ.

Springer, A., Godwin, T., DeWald, L., Hink, J., 1999. Final Project Progress Report Arizona Water Protection Fund Grant No: 96-0003WPF. Arizona Department of Water Resources, Water Protection Fund.

Weissenfluh, D., 2007. The Upper Jackrabbit Restoration (Phase 1) Site Step-by-Step Report Ash Meadows National Wildlife Refuge Nye County, Nevada, Compiled By: Quantell, Inc. for the U.S. Department of Interior, U.S. Fish and Wildlife Service Ash Meadows National Wildlife Refuge.