Ecological restoration of aquatic ecosystems

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Introduction

Restoration is the attempt to return a human-impacted environment to its previous, unaltered condition, which usually involves remove the detrimental factor impacting the ecosystem (Kauffman et al. 1997; Benayas et al. 2009). Ecological restoration is a complex and difficult science, riddled with obstacles, many failures, and few true successes. In of itself, a "successful" restoration is complicated by definition; there are many aspects to a project by which you can judge success or failure. Palmer et al. (2005) names only a few of the features with which a manager can judge a restoration project: cost effectiveness, stakeholder satisfaction, aesthetics, increased recreational opportunities, public education, and advancement of science. Beyond these characters, the physical, chemical, and biological parameters can also be used to determine success or failure. There is also debate among managers and scientists as to what characteristics need to be included in the restoration process in order to improve chance of success, such as the degree of stakeholder involvement and the extent of necessary landscape analysis (Cairns 2000; Bohn and Kershner 2002).

Aquatic systems are some of the most altered ecosystems in the world due to the value of the fisheries industry, recreation, and hydropower. With billions of dollars spent on aquatic ecosystem restoration projects in the USA every year, it is critical to understand how to judge the progress of a project and to determine how to improve success rates (Palmer et al. 2005). Successful restoration projects are often not accomplished the first time around; the best approach may be an adaptive management strategy so that an iterative, learning process will aid in determining the best strategies for ecological restoration.

Lakes/reservoirs

Lakes and reservoirs often function as population centers, subsequently receiving substantial anthropogenic alterations and impacts. Two of the most common causes of management intervention and restoration of lakes and reservoirs is the introduction of invasive species and cultural eutrophication (Cooke et al. 1986). Treatments to correct for these are costly and often do not result in long-term success (Cooke et al. 1986; Sondergaard et al. 2007).

Invasive species

Vectors of exotic species introductions include ballast water, hitchikers, or deliberate introduction, and secondary dispersal via manmade structures (i.e., canals) (Ruiz and Carlton 2003). Ballast water has brought a number of invasive species to the Great Lakes, such as zebra and quagga mussels *Dreissena* spp., round goby *Apollonia melanostomus*, tubenose goby *Proterorhinus semilunaris*, ruffe *Gymnocephalus cernuus*, and plankton species Spiny waterflea *Bythotrephes longimanus* and fishhook waterflea *Cercopagis pongoi* (Stepien et al. 2002; Roman and Darling 2007). Some of these faunal (mussels and plankton) and macrophyte species (ex. *Hydrilla verticillata*) are easily spread by hitchhiking on boats, boat trailers, and fishing gear (Langeland 1996; Roman and Darling 2007). Other means of introduction and spread are through aquarium dumping and deliberate introduction by anglers (Roman and Darling 2007).

Control or eradication of invasive species includes mechanical, chemical, or biological methods. For faunal species, this usually means electrofishing or rotenone (Cooke et al. 1986). Eradication by these methods is rare and virtually impossible in an open system (Carter and Leonard 2002); however, there is higher probability of successful eradication in small, closed systems (Weissenfluh 2007). For invasive macrophytes such as hydrilla or Eurasian watermilfoil, mechanical removal by harvesting, application of herbicides, and introduction of herbivorous fish (i.e., triploid grass carp) are the most common methods of control. Impacts are temporary, and integrated pest management is necessary for a maintenance control program (Langeland et al. 1996; need source for IPM). Herbivorous insects, such as hydrilla flies, have also been attempted, but without much impact (Wheeler and Center 2001). In reservoirs, some control can be implemented by drawdown (Langeland et al. 1996). Invasive macrophyte species often exhibit rapid growth which also substantially increases control costs (Langeland et al. 1996); furthermore, some invasive aquatic weeds are developing herbicide resistance (Michel et al. 2004). The cost of aquatic invasive species management can rapidly escalate to billions of dollars annually (Pimentel et al. 2005).

Eutrophication

Eutrophication is often caused by wastewater treatment effluent entering the lake or from agricultural fertilizer runoff (Cooke et al. 1986). Anndotter et al. (1999) describes the progression of management strategies on Lake Finjasjon, Sweden, through the 20th century. Historical accounts of the lake showed oligotrophic characteristics, with high water clarity in the 1920s. First signs of eutrophication began in the 1930s when untreated sewage began polluting the lake. Cyanobacteria blooms during the summer season made the lake unsuitable for recreation. In response to the poor water quality, a sewage treatment plant was built in 1949, but proved to be insufficient and cyanobacteria blooms worsened. The treatment plant was upgraded in the 1960s, but any improvements were compensated for by the growing population. By the 1970s, managers had considered a range of alternatives- including relocating the discharge downstream- but settled on rebuilding the sewage treatment plant in 1979. Improved conditions were not seen. Reassessment in the 1980s indicated internal cycling and release of phosphorous by anaerobic sediments was the cause of continued eutrophication, and two alternatives were offered: dredging or sediment denitrification. Dredging was attempted, but unfortunately ineffective.

Finally in the 1990s, a new strategy took form. Modeling phosphorus load with various alternative actions investigated whether biomanipulation would be a viable option of treatment. The hypotheses were that a top-down effect on phytoplankton by cyprinid reduction, and the further decrease of external nutrient loading would improve lake conditions. The main focus of the restoration project was to decrease the phytoplankton biomass during the warm seasons to reduce internal loading. Cyprinid reduction commenced from 1992-1994 by trawling, and piscivorous fish were also stocked into the lake. To address external nutrient loading, managers reached out to stakeholders and implemented fertilizer buffer zones around streams. Finally, a wetland was constructed to reduce phosphorus loading in the effluent of the sewage treatment plant. By 1994-1995, fish community composition had improved from mostly cyprinids to an equal ratio of planktivorous and piscivorous fishes. Phosphorus loading decreased by 25%, internal loading decreased, water clarity increased, and submersed macrophytes recolonized. With improved lake conditions, this lake will now be accessible for recreational purposes. This study demonstrates that multiple management strategies were necessary in order to effectively treat the lake for extensive eutrophication.

Rivers

Historically, the modification of rivers and streams has been for the benefit of human society, such as hydropower, transportation, flood control, and agriculture (Kauffman et al. 1997). Thus, riparian zones in the United States have been impacted enormously by direct anthropogenic alterations through channelization, road and bridge construction, forest harvesting, or indirectly by livestock grazing and non-native species introduction (Kauffman et al. 1997). These impacts have caused a decline in aquatic and riparian habitat quality.

Fish passage is critical to the persistence of native species in order to maintain appropriate spawning habitat and genetic mixing (Letcher et al. 2007). The construction of dams, bridges, and culverts can hinder fish migration by blocking streams, increasing stream flow beyond swimming capabilities, or raising outflow height higher than leaping abilities (Mihuc et al. 2008). There are many states implementing fish passage assessments to determine where management actions may be necessary (Mihuc et al. 2008). The Lake Champlain Research Institute in northeastern New York conducted a study assessing almost 50 stream crossings to evaluate fish passage through the Adirondack Park (Mihuc et al. 2008). Approximately 27% of the stream crossings were found to have medium or high priority for management action (i.e., modification or replacement); the inability for fish to pass through one culvert or bridge can make an entire watershed inaccessible to the population (Figure 1) (Mihuc et al. 2008). This not only limits available habitat, but can have genetic consequences by segregating populations. Beyond just these results, the learning process of stream crossing assessment proved valuable in engaging stakeholders and local, state, and federal workers in a workshop to discuss management actions and the evaluation process to encourage further study in other watersheds throughout the state.

Streams

The diversion of stream channels for agriculture and introduction of non-native species for aquaculture has caused detrimental effects on desert spring systems in the American Southwest, including the extirpation of endemic and endangered aquatic species (Kodric-Brown and Brown 2007). Due to the rapid decline of endemic species, many spring systems have are now encompassed in federal refuges, such as the Desert National Wildlife Refuge Complex which includes four refuges throughout southern Nevada (FWS 2012). At Ash Meadows National Wildlife Refuge (AMNWR), restoration several spring systems have improved endemic fish populations. The Fairbanks Spring system was a site of extensive anthropogenic alterations via channelization for agriculture and invasive species introduction. Endemic fish species such as the Ash Meadows Amargosa pupfish (*Cyprinodon nevadensis mionectes*) are in decline, and the Ash Meadows speckled dace (*Rhinichthys osculus nevadensis*) were extirpated from the system (Baldino 2010). Both species are now listed under the Endangered Species Act. The Ash Meadows speckled dace were historically found in many of the same springs as the pupfish, but now only found in two (Baldino 2010). To recover these species, an interdisciplinary team of fish biologists, geologists, hydrologists, geneticists, and ecological consultants met to determine the best approach to the restore the Carson Slough. The Ash Meadows Recovery Implementation Team (AMRIT) decided that restoring the stream system to its historic hydrologic processes was necessary. Prior to channel reconstruction, exotic fish species and non-native vegetation were removed and ecological consultants were contracted to design the new spring system to resemble historical routes (Baldino 2010). In 2009, the stream system was diverted into outflow channels which historically fed into the western side of the Carson Slough

(Figure 2) (Baldino 2010). During this process, several public events were held for pupfish and endemic snail translocation from the old channel to the new channel. Volunteers contributed 297 hours over three days to salvage a total of 3,250 pupfish and approximately 12,000 endemic snails (Baldino 2010). Furthermore, over 2,700 non-native crayfish were removed. Following the volunteer events, AMNWR staff also salvaged another 14,793 pupfish and over 93,000 endemic snails (Baldino 2010). The newly created channels are meant to be dynamic in nature to adjust to flood events, sediment deposition, and encroaching vegetation (Baldino 2010). Within the channels, microhabitats were formed to suit both, pupfish and dace preferences (pools and riffles/runs, respectively). Following water diversion to the new stream channels, extensive revegetation efforts with native grasses (N=9,000), willow poles (N=700), and seeding was implemented (Figure 3) (Baldino 2010). The speckled dace were also reintroduced, doubling their current range (Baldino 2010). Initial monitoring of the system is positive for native vegetation and fish species populations; trapping efforts have confirmed dace reproduction within the new channel system (Baldino 2010).

The Ash Meadows Recovery Implementation Team demonstrates that an interdisciplinary group of professionals is valuable in considering all aspects of restoration efforts that contribute to a successful restoration project. Additionally, the volunteer events were an effective method for stakeholder engagement and support in the project.

Springs

Desert springs are unique and special ecosystems, however they are often exploited by humans because of short water supplies in arid environments (Barquin and Scarsbrook 2007). Barquin and Scarsbrook (2007) describe springs as an “ecotonal” habitat because they occur at the interface of groundwater, surface water, and terrestrial ecosystems. Given their remoteness and disconnectedness of other aquatic habitats, many species found in desert springs are endemic, including fishes and invertebrates (Sada 1996; Barquin and Scarsbrook 2007). Threats to springs include groundwater/aquifer depletion, agriculture, recreational development, and exotic species introduction (Barquin and Scarsbrook 2007; Kodric-Brown and Brown 2007).

As stated previously, Ash Meadows National Wildlife Refuge scientists and managers are working to reconstruct spring outflows to their historic paths and character. Additionally, staff is also working towards exotic species eradication or control throughout the refuge. At least one or more aquatic nuisance species (ANS) is found in almost every spring on AMNWR. A few ANS found on the refuge are the red swamp crayfish *Procambarus clarkii*, western mosquitofish *Gambusia affinis*, and red-rimmed melania *Melanoides tuberculatus* (Bradshaw 2010). These invasive species are extremely persistent and difficult to eradicate due to life history strategies and wide tolerance ranges (Bradshaw 2010).

With extensive and careful planning, exotic species have been eradicated from at least two springs on AMNWR. At Fairbanks Spring, rotenone was applied to eradicate convict cichlid *Amatitlania nigrofasciata* and mosquitofish; at School Springs, a combination of methods was necessary to eradicate crayfish and mosquitofish from this system (Weissenfluh 2008ab; Weissenfluh 2010). Rotenone application must be implemented cautiously due to the presence of endemic and endangered fishes. To use this method, large salvage events prior to chemical application are conducted to remove as many native fishes as possible. It is extremely difficult to eradicate crayfish from an aquatic system due to their resilience to rotenone and burrowing capabilities (Bradshaw 2010). However, a combination of methods may offer the best chance of crayfish eradication (Bradshaw 2010). At School Springs, the springhead outflow was diverted to allow the concrete ponds to dry; following this, mechanical habitat modification/destruction may have eradicated burrowing crayfish (Weissenfluh 2008ab). No mosquitofish or crayfish have been found at School Springs since the restoration, and pupfish are thriving in their new habitat (Weissenfluh 2010). Monitoring of the site continues.

Springs provide high biodiversity and aesthetic value (Barquin and Scarsbrook 2007). Therefore, restoration of springs is wide spread from southeast United States to the desert southwest, and Australia (Barquin and Scarsbrook 2007; Kodric-Brown and Brown 2007).

AMNWR is a model for spring restoration efforts; with careful planning, diverse professionals, and persistence, successful restoration is possible.

Adaptive management

Adaptive management (AM) is a framework for structured decision making in a dynamic decision making process. It embraces the inherent uncertainty of system response to management actions by experimentation, learning, and adapting to outcomes in a positive feedback mechanism (Figure 4). The concept of adaptive management was founded in the 1970's by Walters and Hilborn (1978) and Holling (1978), and is applied to a range of resource problems (Murray and Marmorek 2003).

There are two types of adaptive management: active and passive. The two strategies differ by their approach and emphasis in the reduction of uncertainty (Williams 2011). Simply stated, active AM is the implementation of multiple management strategies in an experimental fashion in order to reduce uncertainty of the system by learning. Passive AM focus is on the system response to a management decision which is based on the current state of the system at a given time, with learning a secondary benefit and at a much slower pace than with active AM (Williams 2011). Both strategies are valuable tools, and deciding which method is most appropriate for a situation largely depends on the system state/type, the importance/limitations of cost, uncertainty, learning, and time scale.

The first step in an adaptive management process is assessment of the situation. It is critical to correctly diagnose the management problem in order to implement a correct and effective management strategy (Cooke et al. 1986). Assessment includes clearly defining causes of the problem (possibly through preliminary research), explicitly stating objectives of the project, and expressing uncertainties (Murray and Marmorek 2003). Modeling possible alternatives is also an important aspect of assessment to better understand which alternatives are best for experimentation (Walters and Hilborn 1978). Natural resource problems are often contentious between scientists/mangers and stakeholders. Engaging stakeholders in the process will aid in acceptation of the management plan and is critical in the success of the project (Cairns 2000; Allen and Gunderson 2011).

The second step in adaptive management is the design of the project. The spatial and temporal scopes must be clearly defined in order to adequately design a management strategy (Wissmar and Beschta 1998). The design of a project encompasses the actions that will be taken, testing of hypotheses about uncertainties, site assessments, and plans for follow-up monitoring (Murray and Marmorek 2003). Many authors stress the importance of historical literature and documentation in order to design a system in a way similar to its original state (Kondolf and Larson 1995; Shields et al. 2003; Palmer et al. 2005). Depending on the project, it may be necessary to consult hydraulic engineers or ecological consultants for system reconstruction (Shields et al. 2003).

The third step in adaptive management is implementation. This involves the on-the-ground work of restoration efforts. Murray and Marmorek (2003) emphasize that for successful adaptive management, the “implementers” must understand the specific action(s) that managers have chosen in part of the experimental design. Any actions or deviations from plans must be well documented so that the system response is adequately appropriated to the management strategy.

The fourth and fifth steps in adaptive management are monitoring and evaluation. Monitoring is critical in order to evaluate the ecosystem response to the management strategy for future management alternatives. Monitoring includes assessing whether the actions were taken as prescribed, to learn whether the actions enhanced the system, and to tests hypotheses about the system (Murray and Marmorek 2003). Monitoring should be focused for specific management questions which can be addressed through evaluation of the data obtained (Barquin and Scarsbrook 2007).

The last step in the adaptive management closed-loop system is adjusting. This is where the “adaptive” aspect of AM comes into play: based on what is learned through monitoring and evaluation, models will be updated with data and new uncertainties, and new alternatives will be presented (Walters and Hilborn 1978; Murray and Marmorek 2003). Learning about the system response will enable managers to better predict optimal management strategies and outcomes.

Application

Since lakes are large-scale spatially, multiple manipulations are not possible (unless managing multiple lakes). Therefore, passive adaptive management is probably more common in lake restoration projects. The Lake Finjasjon case study demonstrates that with the implementation of a structured decision-making process (i.e., clearly defining objectives, uncertainties, and alternatives; modeling, implementation, monitoring, and evaluating), success is more likely than previous attempts on the system. Engagement of stakeholders also proved to be important in the recovery of this lake. Since a single lake is more difficult to implement active adaptive management, an experimental-fashion implementation of multiple management strategies was a valuable and effective approach to this management problem. As monitoring continues, data can be used to update models and inform additional management decisions on this lake.

Several authors argue various aspects of river/stream management that are critical to restoration success, such as a watershed-based or landscape approach (Bohn and Kershner 2002; Wissmar and Beschta 2002), clearly defined project objectives (Shields et al. 2003), the use of historic information (Kondolf and Larson 1995; Palmer et al. 2005), modeling in project design (Palmer et al. 2005), incorporating uncertainty (Pess et al. 2003), and engagement of stakeholders (Cairns 2000; Shields et al. 2003). Following an adaptive management framework incorporates all these aspects into the recovery plan of an aquatic system. Unfortunately, Bernhardt et al. (2005) gathered over 3,700 river restoration projects to investigate the common characteristics of successful projects to find that only 10% of projects have follow-up monitoring programs. Since most projects do not conduct monitoring to evaluate the consequences of restoration actions, it is difficult to assess whether projects were successes or failures, and inhibits learning to improve practices.

Ash Meadows National Wildlife Refuge offers a model from which many restoration efforts – not just desert springs – can take lesson. The detailed preparation, interdisciplinary recovery team, stakeholder outreach, and follow-up monitoring are all extremely important for the success of a restoration project. Monitoring is vital in the learning process; what is learned through one project can be applied to the next.

Conclusion

Aquatic ecosystem degradation takes many forms, as do restoration efforts. Using the adaptive management framework, restoration efforts will have a greater chance of success in the long-term. Palmer et al. (2005) states, "restoration success should not be viewed as an all or nothing single endpoint, but rather as an adaptive process where iterative accomplishments along a predefined trajectory provide mileposts towards reaching broader ecological and societal objectives." However, when possible, it is always better to avoid irreversible damage to a system by prevention of over exploitation (Cairns 2000); this will become continuously challenging as populations and needs grow for natural resources.

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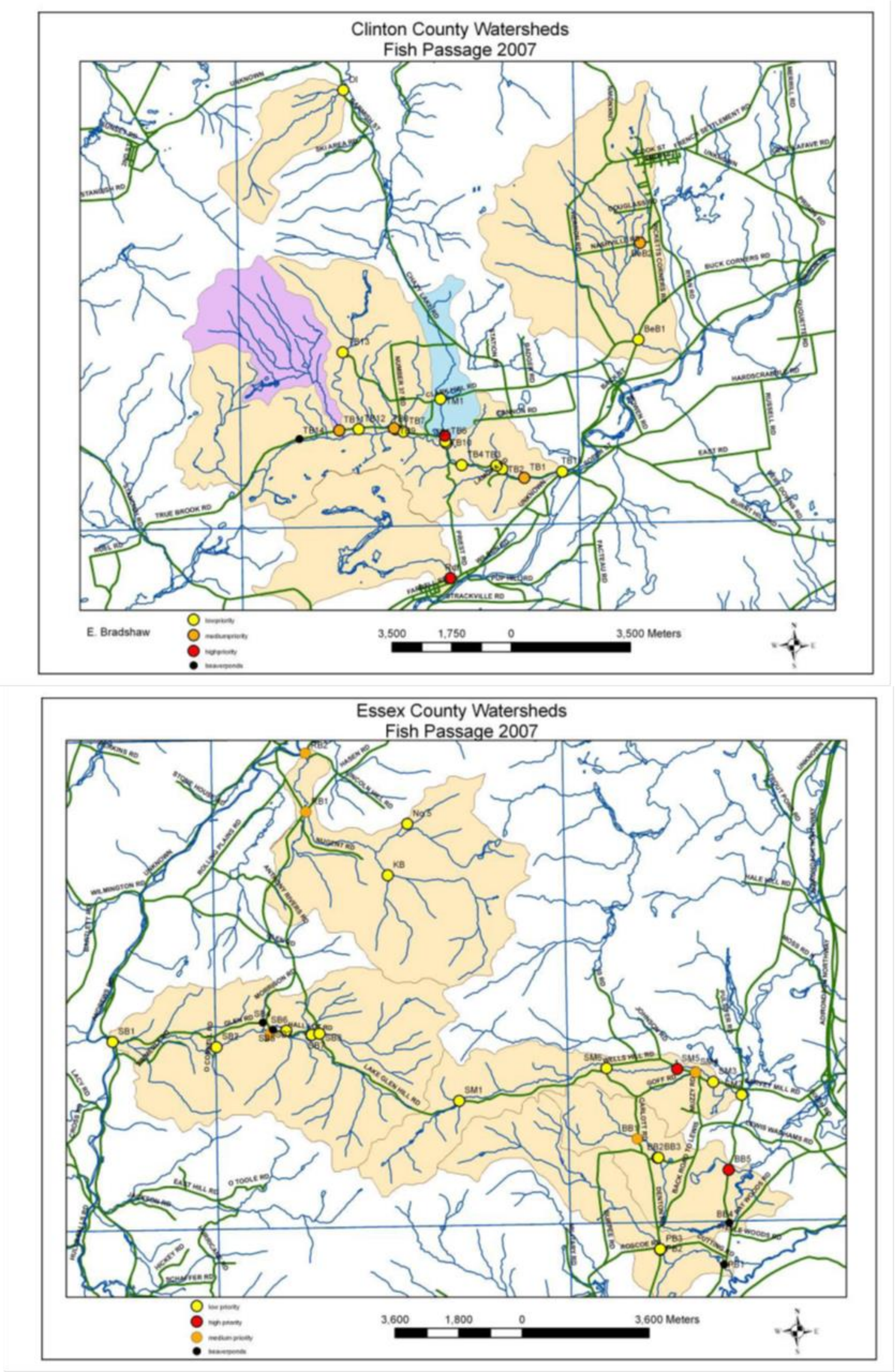

Figure 1. Road crossing ratings in Clinton (top panel) and Essex (bottom panel) counties, New York. Yellow sites are low priority, orange sites are medium priority, and red sites are high priority.

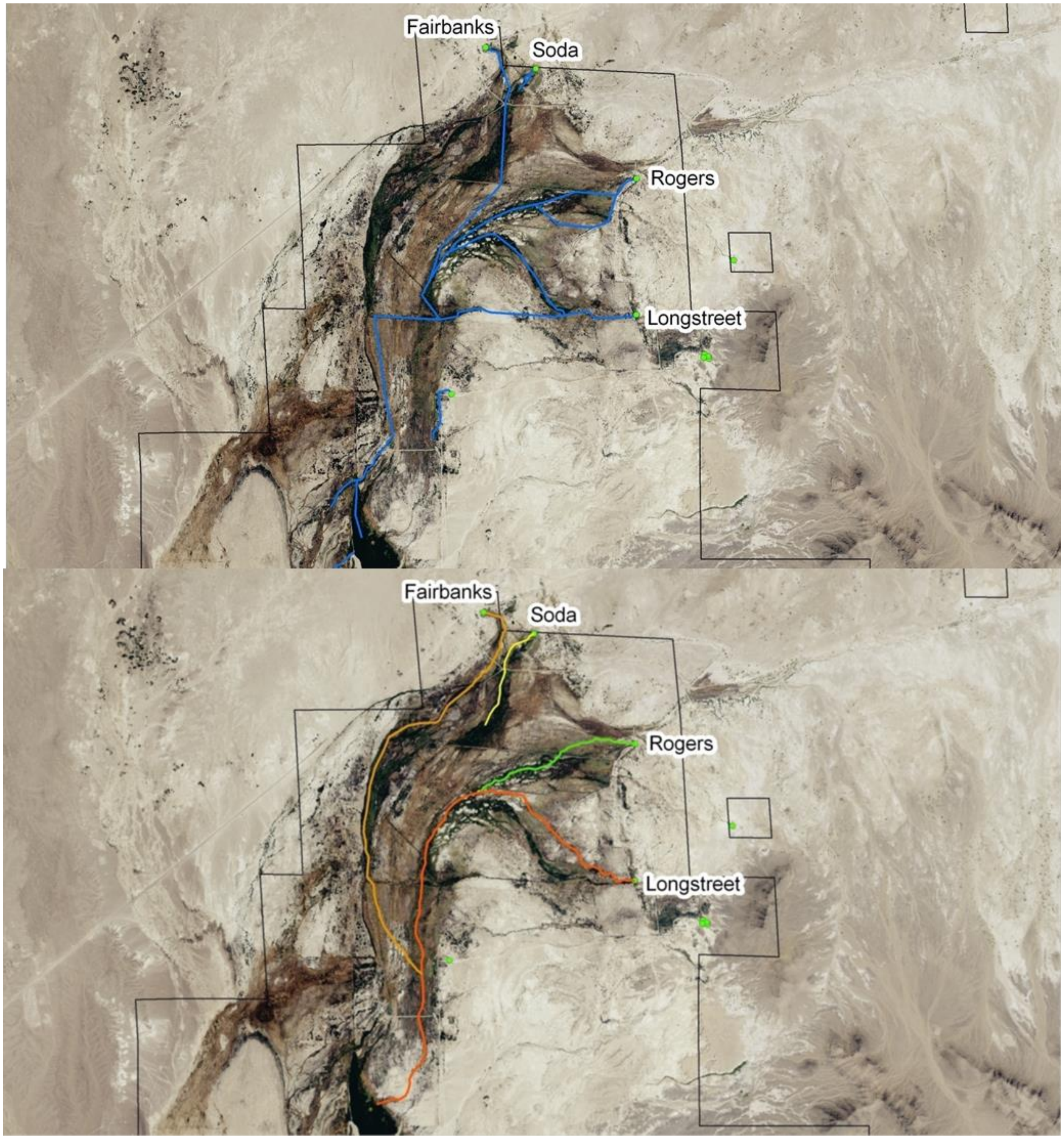

Figure 2. Spring systems of the Carson Slough before (top panel) and after (bottom panel) restoration. Ash Meadows National Wildlife Refuge, Amargosa Valley, Nevada.

Figure 3. Fairbanks Spring system revegetation of newly constructed channels. Ash Meadows National Wildlife Refuge, Nevada.

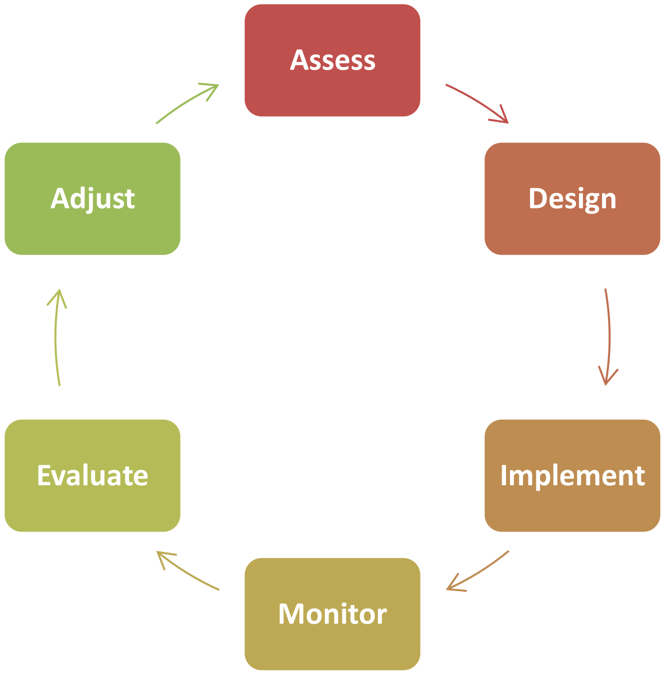

Figure 4. Adaptive management feedback mechanism