Chapter 8: Meadow Management and Treatment Options

Jeanne C. Chambers and Jerry R. Miller

Introduction

Restoration and management objectives and approaches are most effective when based on an understanding of ecosystem processes and the long- and short-term causes of disturbance (Wohl and others 2005). As detailed in previous chapters, several factors are critical in developing effective management strategies for streams and their associated meadow ecosystems in the central Great Basin. First, many streams and/or valley floors are still responding to a major drought that occurred almost 2000 years BP that stripped the hillslopes of available sediment and resulted in a natural tendency toward incision. Second, human disturbance has increased both the rate and magnitude of this incision. Since settlement of the Great Basin region in 1860, upland watersheds have undergone significant changes in land use, vegetation cover, and climate that have altered the hydrologic and sedimentologic regimes of the axial drainage system and its associated meadows. Many meadow complexes are at increased risk of incision because they often are located on valley floors with stepped profiles caused by side-valley alluvial fans in the longitudinal profile. While some of the stream systems and their associated meadow complexes have adjusted to the current hydrologic and sedimentologic regimes and are now in a quasi-equilibrium state, others are in a nonequilibrium state and are still actively incising. Consequently, return to pre-incision conditions is an unrealistic goal for these dynamic systems.

Chambers and others (2004a) defined the goal of restoration and management activities as re-establishing and maintaining sustainable fluvial systems and riparian ecosystems that exhibit both characteristic processes and related biological, chemical, and physical linkages among system components (modified from Natural Research Council 2002). In this context, sustainable stream systems and meadow complexes exhibit natural variability yet maintain characteristic processes, including rates and magnitudes of geomorphic activity, hydrologic flux and storage, biogeochemical cycling and storage, and biological activity and production (Christensen and others 1996; Wohl and others 2005). Management objectives and approaches for central Great Basin meadow complexes must acknowledge the dynamic character of these ecosystems and focus on the current potential to support a given set of geomorphic, hydrological, and ecological conditions over a reasonable period of time (Chambers and others 2004a). The primary management objective should be to maintain and enhance meadow complexes by preventing further incision and avulsion where possible and by improving ecological conditions.

The characterization of meadow complexes in the central Great Basin (Chapter 7) and discussion of basin sensitivity to disturbance (Chapter 5) illustrate that not all systems have responded similarly to natural and anthropogenic disturbance. Meadow ecosystems exhibit varying degrees of stream incision, groundwater lowering, and riparian vegetation degradation based on their geomorphic and hydrologic controls and disturbance history. Management plans must be based on careful assessment both of the dominant geomorphic and hydrologic controls and of the causes of disturbance at watershed, valley segment, and site scales. These plans also must consider the current magnitude of incision or degradation and the potential for stream stabilization and vegetation management. Important elements of meadow management are prioritizing which meadows to treat, establishing objectives on a meadow-by-meadow basis, identifying and selecting treatment options, evaluating success through monitoring, and using the results for adaptive management. Each of these tasks is briefly discussed below.

Prioritizing Meadow Management

This report provides insights into the geomorphic, hydrologic, and biological processes that function within meadow complexes in the central Great Basin. These include: (1) a basic understanding of the potential for future meadow degradation; (2) a description of the processes by which the meadows are degraded; and (3) a means of assessing the likelihood of success for various treatment options. At larger scales, stream incision and its effects on meadow ecosystems are influenced by their position in the watershed, the magnitude and rate of runoff, the geomorphic and hydrologic sensitivity of the meadow, and the linkages between the groundwater system and the stream channel. Chapter 7 provides a categorization of central Great Basin watersheds based on data collected from 56 meadows in upland watersheds in 2005 and 2006. A summary of the variables and methods of measurement are in table 7.1. The different meadow groups and their general characteristics are in table 7.5, and the averages for the most influential variables are in table 7.2. This information is a useful starting point for assessing current meadow conditions and the potential for future degradation. A metadata file and the data files for each meadow have been archived through the USDA Forest Service, Rocky Mountain Research Station and are available at: http://www.fs.fed.us/rm/data_archive/dataaccess/Central_NV_Meadow_Characterization.shtml.

The files also can be accessed by following the links provided in the data archive: http://www.fs.fed.us/rm/data_archive. The central Nevada meadow characterization can be accessed by following the Data Access link. Prior to using these data, one must verify that the longitudinal and cross-sectional profiles and meadow characterizations are accurate because intervening high flows may result in knickpoint migration and other types of incision or avulsion. Also, inappropriate livestock use can influence meadow species composition.

Determining the likelihood of future meadow degradation and the potential for recovery requires an understanding of the geomorphic and hydrologic sensitivity of the meadows. The framework for understanding meadow sensitivity to disturbance is provided in Chapters 3 and 4, and its use is discussed in Chapter 5. Specifically, a set of factors is presented that can be used to determine the likelihood for geomorphic change and the probability that these alterations will result in significant declines in groundwater levels and, thus, changes in vegetation. Analysis of the sensitivity of individual meadows requires examining the factors discussed in table 5.1. This can be accomplished by using cartographic and remotely sensed data and by making field visits. Because meadow complexes are groundwater features that may or may not be closely tied to the surface channel system within the meadow complex, determining the linkages between the channel and groundwater flow system is of utmost importance in assessing the effect of channel incision on groundwater levels and vegetation types and distribution. A means of assessing surface water and groundwater interactions is described in Chapter 4 and examples are provided in table 4.2. This approach generally provides enough information to determine if major groundwater responses to incision (as well as various treatments) are likely.

Objectives and Design Criteria for Stream Stabilization and Meadow Vegetation Management

An understanding of the geomorphic, hydrologic, and biological processes within the meadows can be used to define a set of realistic management objectives for a given meadow. Developing these objectives is required to determine what constitutes project success, and it should be accomplished before any stream stabilization or vegetation management project is initiated. One must also formulate design or success criteria. Design (success) criteria are quantifiable benchmarks that specify how the various components of the work should perform and are used to ensure that the objectives of the project are met. Design criteria may include measurable limits to headcut or knickpoint advancement, bank stability, flood conveyance, and/or the aerial extent of specific meadow vegetation types (Skidmore and others 2001). Project success often depends on the effort that goes into developing design criteria because they are a guide to what needs to be accomplished for each component of the project (Miller and Orbock Miller 2007). Moreover, the process of constructing design criteria is likely to provide important insights into whether a particular objective can be achieved given the biophysical processes operating at the site.

Identification and Selection of Treatment Options

Establishing a General Framework

In recent years, managers have increasingly relied on channel evolution models (CEM) (Schumm and others 1984; Simon and Hupp 1986; Simon 1989; Rosgen 1996, 2001, 2006) to evaluate the magnitude of incision and the evolutionary changes in channel morphology during the entrenchment process and to identify potential management options. These models, which portray a semi-systematic series of geomorphic events once incision has begun, are not always applicable to upland drainages in the central Great Basin. In these drainages, incision is often characterized by episodes of avulsion and/or cyclical periods of gully erosion and deposition. For management purposes, it is useful to first classify the drainages according to their morphologic characteristics and dominate erosional and depositional processes. A simplistic approach to classification is to separate basins into two groups: those that exhibit riparian corridors that possess a discontinuous drainage system and those that possess an integrated drainage network. In the former, the valley floor is usually characterized by short reaches of stream channel (tens to a few hundred meters) that are incised into the valley fill, separated by unincised reaches that are devoid of a recognizable channel system (fig. 8.1). The dominant processes that are operating in these areas (such as in Indian Valley) are gully development and headcut advancement (Chapter 3). In the latter, the riparian corridor contains a continuous channel network throughout the basin, although flow within the channel may be locally ephemeral, particularly during the late summer months. The integrated drainages may be further subdivided into those exhibiting (1) low to moderate depths of incision (zero to two times bankfull channel depths), (2) highly incised channels (more than two times bankfull channel depths), and (3) "fully" incised channels that are currently in a state of equilibrium. The separation of these channels on the basis of incision is arbitrary, but it provides a useful system to discuss potential management options that can be applied to maintain and/or improve meadow ecosystems.

Low to Moderately Incised Channels. If the stream exhibits a limited degree of incision, it may be possible to use in-stream structures and bank stabilization measures to stabilize the stream channel. Channels with minor incision occur within all meadow groups but are most common in the smaller stream channels that occur in meadow Groups 3, 4, and 5 (Chapter 7). Stabilizing channels and knickpoints when they first appear can prevent knickpoint migration and can minimize the effects of other factors that contribute to stream incision during episodic high flows. Channel stabilization is often sufficient to maintain meadow vegetation.

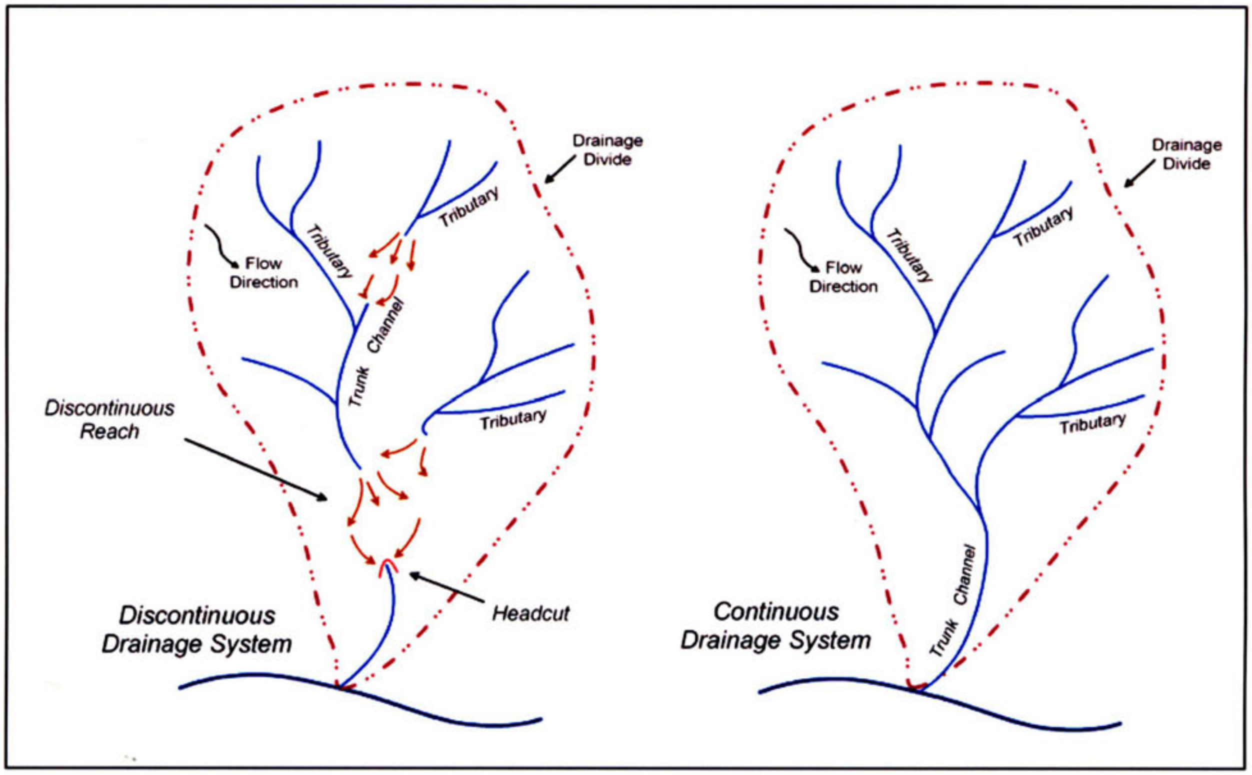

Figure 8.1. Schematic diagram of discontinuous (top) and continuous (bottom) drainage basins. Continuous drainages are thought to have had an integrated, axial drainage network throughout the late Holocene.

Highly Incised Channels. Highly incised channels are found in all meadow groups but are most pronounced in Groups 1 and 2 (Chapter 7). Stream stabilization measures are possible but must be based on careful assessment of (1) the geomorphic and hydrologic sensitivity both within and upstream of the meadow and of (2) the linkages between the groundwater system and stream channel. Structures should be designed to accommodate geomorphic irregularities, like side-valley alluvial fans, episodic high flows, and the predominantly high gradients that occur in these systems. The primary objective of installing in-stream structures is to prevent or minimize further incision of the main channel, prevent incision of spring channels, and maintain existing springs and seeps. In some cases, it may be possible to stabilize the stream banks with plugs or transplants of meadow vegetation. The net effect of stabilizing stream channels can be to maintain or improve existing meadow vegetation if a progressive decrease in water tables can be halted. Once incision has been stopped, active vegetation management can be used to improve ecological conditions.

Fully Incised Channels. In cases where stream channels are fully incised and are now in a state of equilibrium, as sometimes occurs in Group 1 and 2 meadows (Chapter 7), the stream channel typically has reached a stable configuration, although minor adjustments may occur as the stream works to expand its floodplain. It is seldom ecologically or economically feasible to reconstruct or elevate these streams. If groundwater tables have dropped, as indicated by shrub encroachment and drier vegetation types, it may be possible to actively manage the area to maintain meadow vegetation based on understanding the relationships between groundwater tables and riparian vegetation, as described below. It may not be possible to return these areas to the large, meadow complexes they once supported but, if water tables are sufficiently high, active vegetation management can be used to maintain them as smaller meadow complexes or dry meadows. Maintaining meadow vegetation within riparian corridors allows a mosaic of shrub- or tree-dominated areas and meadow complexes that more closely resembles predisturbance conditions and that provides important wildlife habitat.

General Considerations for Stream Stabilization

The approaches used for stabilizing minimally incised and highly incised streams must be aligned with the dominant mechanisms of incision. These mechanisms can vary among meadows, or even among areas within a given meadow. In some cases, incision may involve the grain-by-grain entrainment of channel bed sediment; in other instances, incision may be related to upstream migration of knickpoints generated by a lowering of the base level. Incision also may occur by means of groundwater sapping and headcut retreat. Areas affected by these different incision processes require their own set of objectives, design criteria, and treatment strategies.

While incision is likely to be the predominant problem of concern, it also is important to recognize that meadow complexes are groundwater features, and other geomorphic and hydrologic processes that operate in these environments must be considered in project design. The most important of those processes are: avulsion, breaching of confining units, and erosion by groundwater processes.

Avulsion

Although a stream may be incised, the instantaneous influx of coarse sediment to the meadow from upstream areas may lead to channel avulsion and entrenchment of a new stream segment in a completely different part of the meadow complex. In-stream structures and changes in riparian vegetation alter flow resistance and transport processes and may increase the potential for channel aggradation and avulsion. Thus, the sensitivity of the meadow to avulsion processes should be considered at every site where biophysical treatments are applied.

Breaching of Confining Units

Hydrologic data from instrumented meadows demonstrate that fine-grained (silt and clay-rich), confining units are an essential component of meadow development. Breaching of these units has the potential to result in major changes in the subsurface flow system and drainage of the meadow complex. Thus, management strategies must consider how any treatment will affect surface and subsurface flow systems and their interactions. Approaches like channel reconstruction or plug and pond methods that require excavation of alluvial materials are probably not appropriate for most central Nevada meadow systems and should be applied with extreme care.

Erosion by Groundwater Processes

Groundwater sapping (seepage erosion) has been observed to dramatically affect the riparian corridor of these upland catchments where there is ample water and the alluvial valley fill is composed of highly permeable sand or grus-sized sediment. Even minor modifications to these systems may lead to unexpected, deleterious consequences such as formation of deep gullies.

In-Stream Structures and Aquatic Habitat Enhancement Devices

In-stream structures and other aquatic enhancement devices were initially used at least a century ago to improve fish habitat in the United States (Beschta and others 1992; Thompson 2005). Since then, Federal agencies have relied heavily on the use of these structures to improve aquatic and riparian habitat (Frissell and Nawa 1992; Thompson 2005).

These devices fall into four broad categories (which are not mutually exclusive): grade control devices, habitat cover structures, bank protection devices, and flow deflectors or concentrators (Miller and Kochel 2008, 2010). Grade control structures are perhaps the most widely used and are intended to maintain the bed of the channel at its present elevation. These devices are typically composed of logs or large boulders and are installed within the channel in such a way as to inhibit channel bed erosion. Historically, these structures included various types of dams and/or weirs, including check dams, K-dams, jack dams, wedge dams, log or rock sills, and log drop structures (Seehorn 1992). Cover structures are intended to provide or improve aquatic habitat, particularly for fish. They include a wide range of devices, the most common of which are bank lunkers or cribs, raft and boom covers, log-and-brush shelters, and felled trees. Bank protection devices are designed to reduce the magnitude and rate of bank erosion. Until recently, these devices lined part or all channel margins with some form of erosionally resistant material and include A-Jacks, dirt or rock filled gabions, rock or crib walls, and rip-rap and stone toe revetments. Most flow deflection devices protrude out from the stream bank and are intended to narrow the channel, protect banks from erosion, or create pools (and pool habitats) through redirection and concentration of flow. The most common types are single or double wing deflectors and spurs. Flow deflectors also include various types of boulder placements, a practice that involves placing large boulders along the banks or within the channel to create localized zones of scour.

Since the early 1990s, there has been an attempt to restore or rehabilitate at least part of the structure, function, and diversity of the historic river (Riley 1998). Many projects use extensively hardened habitat improvement devices, including a new generation of rock or log structures that are endorsed by Rosgen and his colleagues (Rosgen 2001, 2006), including cross-vanes, J-hooks, rock (or single arm) vanes, and W-weirs. These newly designed in-stream structures are intended to decrease near-bank velocities and shear stress by redirecting flow away from banks. Thus, their purpose is to reduce bank erosion and improve aquatic habitat by creating localized zones of channel bed scour and pool formation.

The uses, design, and installation of older habitat improvement devices, which are used extensively, have been thoroughly described in a number of manuals, including Arthur (1936), USDA Forest Service (1952), and Seehorn (1985, 1992). Use and design of more recently developed in-stream rock and log structures are described in Rosgen (2001, 2006). These manuals should be consulted to gain additional information on these structures.

Use of In-Stream Structures

A review of the past performance of in-stream and other improvement structures, combined with an understanding of erosion processes in Great Basin meadows, indicates that stream stabilization methods must be tailored to the specific characteristics of the system. As indicated in previous chapters, meadows often are located upstream of side-valley fans and are characterized by convexities in long channel/valley profiles. Where this occurs, installing grade control structures at the toe of the fan may effectively stabilize the

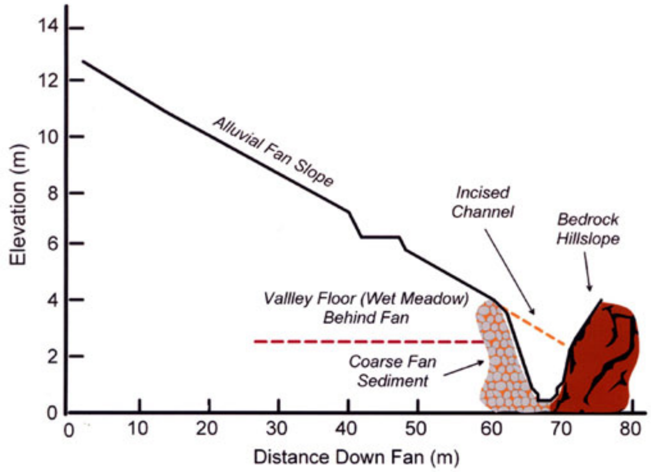

Figure 8.2. Radial fan profile near Kingston 3 meadow in Kingston Canyon. Erosion around structures within and immediately upstream of the fans is limited by coarse fan sediments and bedrock beneath the hillslope, which reduces the probability of failure.

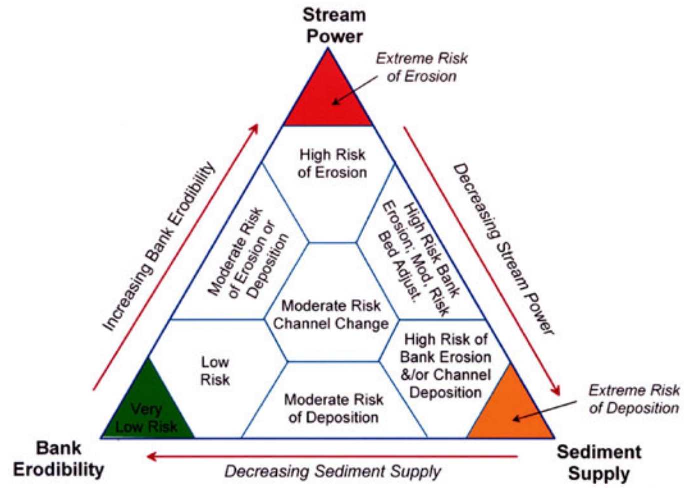

Figure 8.3. Ternary diagram showing the likelihood that instream structures will fail. The diagram is based on detailed assessments of structures in North Carolina and, to a lesser degree, in Virginia and shows that the probability of failure is related to stream power, sediment supply, and bank erodibility (from Miller and Kochel 2008, 2010).

channel. These stream reaches are important local, base-level controls that dictate the magnitude of upstream incision. Inhibiting incision at the toe of the fan, which is generally co-located with a convexity in the longitudinal profile, will limit the amount of future erosion that can occur within the meadow. Erosion around these structures is more difficult as erosion in these reaches often requires the removal of bedrock or coarse-grained colluvial and alluvial fan sediments (fig. 8.2).

The use of in-stream structures and other devices throughout the meadow and upstream of side-valley fans should be used with more caution, particularly where there is evidence of past channel avulsions. Although structures such as rock vortex weirs and cross-vanes are intended to maintain sediment transport through the reach (Rosgen 2001), post-project evaluations in numerous regions of North America (such as British Columbia, California, and North Carolina) have shown that these structures often lead to in-channel deposition (Miller and Kochel 2008, 2010). Along meadow reaches where avulsions occur frequently, use of such structures may lead to channel deposition and flood flows over the meadow surface. This may cause subsequent incision or new channel formation and meadow degradation along a new part of the valley floor.

It also is important to recognize that post-project evaluations have shown that performance of in-stream structures and other habitat improvement devices varies dramatically from site to site (Miller and Kochel 2008, 2010). Variations in performance appear to be partially related to stream channel dynamics. Effectiveness is greatly reduced along channels that are characterized by high stream power, large sediment supplies, and erodible banks (fig. 8.3; Miller and Kochel 2008, 2010). Performance also tends to be much lower along unstable channels that experience changes in channel dimensions or incision. Use of rock gabions to halt ongoing incision in the Hot Creek Mountains resulted in the stream cutting around the structures (fig. 8.4a). Use of log cross-vanes in San Juan Creek resulted in the stream cutting under the structures (fig. 8.4b). Many investigators have noted that in-stream devices will require continued maintenance to prolong effectiveness (Frissell and Nawa 1992; Miller and Orbock Miller 2007). One cannot simply install these devices and expect them to function for long periods of time (multiple years to decades). They will need to be continually inspected and repaired. Given the inherent instability of most upland channels in the central Great Basin, continued maintenance will be particularly important to ensure device effectiveness in meadow complexes.

Use of Headcut and Gully Stabilization Measures

A common form of meadow degradation is development of gullies and upvalley migration of associated headcuts. Gullies are particularly common along relatively steep and narrow reaches of the valley floor, which often characterize downstream areas of meadow complexes. As a result, upvalley gully propagation, primarily by means of headcut advancement, is an especially important management issue. Unfortunately, gullies represent a particularly difficult form of degradation to treat, and it can be argued that effective management strategies have yet to be developed for these systems. Gullies are not only the product of surface flows but they result from the combined effects of both surface- and groundwater (seepage) erosion associated with shallow groundwater levels and layered stratigraphy. Thus, gully treatment must include measures to deal with multiple mechanisms of erosion that may occur at different times

Figure 8.4. (a) Stream avulsion around a rock gabion structure in the Hot Creek Mountains. (b) Incision under an X-vein structure in San Juan meadow. Photos by J. Chambers.

and under different hydrologic conditions. Complicating the problem further, data with which to evaluate the effectiveness of headcut and gully mitigation strategies in meadow complexes in the region are limited.

In general, commonly utilized treatment strategies fall into four categories: (1) using in-stream check dams and weirs to stabilize the base level and to retain sediment; (2) regrading and vegetating the gully banks and headcut to increase channel cross-sectional areas, reduce shear stress, and inhibit bank failure by mass wasting processes; (3) lining the headcut and banks with rock or other erosionally resistant material; and (4) spreading and/or diverting surface flows to reduce the amount of water entering the gully and to limit the concentration and erosive forces of surface flows on the valley floor. Exactly which method is most appropriate depends on the gully's current morphology, its hydrologic and geologic setting, its position and integration within the drainage network, and the mechanisms responsible for headcut migration. Thus, selection of the stabilization approach must be based on a sound understanding of the gully or gully system to be treated.

Some of the most intensively treated gullies to date are located in Indian Valley at the southern end of the Toiyabe Range. Near the mouth of Indian Valley, a number of shallow, discontinuous gullies that terminate upstream in headcuts have entrenched the valley fill within a wide, low-gradient meadow complex. Treatment of these shallow gullies relied primarily on a combination of headcut and bank regrading, followed by placement of large rocks over the regraded area. Treatment likely began following major flood events in the early 1980s, and vegetation associated with the regraded area suggests that the rock has been in place for at least a decade. When used on gullies with limited groundwater seepage and groundwater erosion, we observed that the structures were not affected by any erosion, although it is unclear whether they had been subjected to significant overland flow events. In some locations, however, seepage erosion had undermined the rock, leaving a disorganized array of boulders in the channel bed, while the headcut continued to migrate upvalley. Our qualitative observations suggest that where groundwater seepage is not important, gully regrading combined with localized "rip-rap" may be effective. This approach will be only marginally effective for reducing groundwater erosion and will require repeated maintenance to be effective against surface flows.

Large gullies in Indian Valley often were treated by constructing linear ridges across the valley floor, starting in the mouth of the gully. The intent was to spread surface flows over a larger area, thereby reducing erosive potential. Examination of sequential aerial photographs revealed that the approach was often successful at reducing erosion immediately downstream of the captured gully (i.e., the gully dammed by the earthen ridge) but usually resulted in development of new gully systems on another part of the valley floor (fig. 3.17). In fact, field observations revealed that even minor flow diversions within the meadow complexes could lead to unintended flow concentrations and gully formation elsewhere. Despite the meadows' low gradients and extreme widths, they are extremely sensitive to erosion, and even minor changes in overland flow routes or depths can negatively affects meadow integrity. The difficulty of treating these gullies where both groundwater and surface water erosion are important stresses the need to manage the meadows such that gullies do not form in the first place. Once they establish, there may be little that can be done to rehabilitate the site.

However, not all gully and headcut systems are like those of the stream in Indian Valley. Many tend to be restricted to narrow, steeper reaches of the valley floor. Headcuts in these areas also are likely to be formed by a combination of surface- and groundwater erosion processes. However, in contrast to Indian Valley, where a very large supply of groundwater is continuously available and surface water flows can be enormous, the upstream supply of water to the site in these areas is more variable. Thus, the potential to reduce the rates of headcut advancement may be higher and more closely linked to factors such as upstream water supply, valley width, valley slope, and sediment composition of the valley fill. In very general terms, more water; narrow, steep valley floors; and permeable, non-cohesive sediments will increase the likelihood of headcut advancement as well as the difficulty of treating the problem.

Use of Biotechnical Methods

Stream bank stabilization within meadow complexes can be facilitated using biotechnical methods that focus on the use of live plant materials. Methods for biotechnical streambank stabilization are diverse and typically include the use of living plant material (tree or shrub stems and grass, sedge and rush plugs, or transplants) and inert erosion control materials (natural and synthetic geotextiles, rock rip-rap, log cribs, or coconut fiber rolls). The root systems of living plants increase streambank stability by providing resistance to shallow mass movement. Plant roots can reinforce the soil through tensile fibers in the root mass and anchor the slope through deep root penetration into more stable strata (Gray and Sotir 1996). Actively growing riparian vegetation can increase shear strength by reducing poor pressure (Gray and Sotir 1996). Also, foliage and stems of shrubs and trees on streambanks can decrease flow velocities and dissipate energy by redistributing flow patterns and directions (Li and Eddleman 2002).

A review of biotechnical streambank stabilization methods and their properties and applications is found in Li and Eddleman (2002). The stream environment is often complex, and different types of stabilization may be required for the zones associated with various stream stages. For example, more intensive measures may be required in the zone between average flows and typical high flows and in zones characterized by groundwater sapping. Combining different biotechnical methods, like inert erosion control materials and living plant material, is often most effective. In Kingston 3 meadow, placing coconut fiber rolls in the zone between average flows and typical high flows and planting deep-rooted meadow species effectively stabilized a bare streambank that exhibited groundwater sapping (figs. 8.5a and b).

Information on harvesting, propogating, and planting wetland species that is appropriate for Great Basin meadow complexes is provided in Hoag (2003). Individual riparian species occur within well-defined water table regimes and depths to saturation (Chambers and others 2004b). Success of transplanting "wildlings" or plant materials harvested from the site or propagated in the greenhouse depends on matching water requirements of the species with the period of saturation and available soil water of the stream bank. Plantings are most vulnerable during the first two years of establishment and may require maintenance if high flows occur during the establishment period. Deferring grazing use for two years after bank stabilization is necessary to ensure success of the project.

General Considerations for Vegetation Management

The methods used for vegetation management within meadow complexes depend on the water table regime and the composition of meadow vegetation, as influenced by the disturbance history of the site. As discussed in Chapter 2, the hydrologic regime is the primary determinant of soil characteristics, plant community composition, and dynamics of riparian meadow complexes (Chambers and others 1999; Castelli and others 2000; Martin and Chambers 2001a, 2001b, 2002). A classification of riparian ecological types in the central Great Basin based on climate, landforms, soils,

(a)

(b)

Figure 8.5. Bank stabilization of an area in Kingston 3 meadow using coconut fiber rolls and graminoid plugs from the meadow (a) immediately after installation and (b) three years later. Photos by J. Chambers.

and vegetation identified five meadow ecological types (Weixelman and others 1996). Three of the meadow ecological types are characterized by similar, high water tables and are differentiated based on elevation and soil texture. They are aquatic sedge (*Carex aquatilis*; high elevations), tufted hairgrass (*Deschampsia ceaspitosa*; coarser textured soils), and Nebraska sedge (*Carex nebraskensis*; mid to low elevations and fine textured soils). The remaining two types occur over a gradient of decreasing water table depth and are the mesic (mesic graminoid) and dry (dry graminoid) meadow types. An additional ecological type often occurs at the periphery of graminoid meadow complexes and is characterized by lower water tables: sage meadow (basin big sagebrush/Great Basin wildrye; *Artemisia tridentata* ssp. *tridentata*/*Leymus cinereus*). At higher elevations, a similar ecological type occurs that is dominated by mountain big sagebrush (*A. tridentata* ssp. *vaseyana*) and Great Basin wildrye. "Average" water table depth and relative variability have been determined for the wet (*Carex nebraskensis*), mesic, dry, and sage meadow ecological types (fig. 8.6; Chambers and others 2004b). Wet and mesic meadows have the highest water table requirements and tolerate the least variability in water table depth (Castelli and others 2000). Stream incision within meadow complexes has the potential to lower the base level of groundwater discharge into the stream (depending on the hydrologic setting), cause lowered water tables, and result in a change in the composition of meadow vegetation in areas affected by lower water tables (Chambers and others 2004a, 2004b). As a result, big sagebrush and other upland species can encroach and eventually dominate in areas formerly characterized by meadow vegetation (Chambers and Linnerooth 2001; Wright and Chambers 2002).

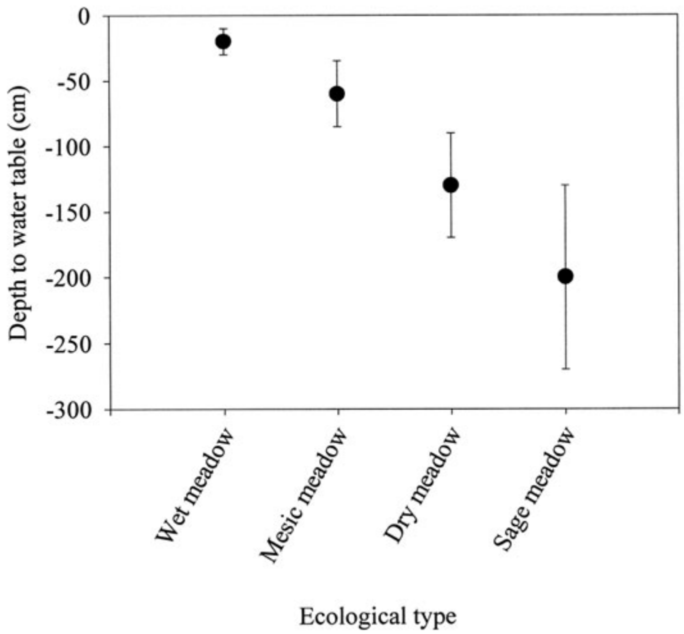

Figure 8.6. The water table depths (means ± S.E.) for meadow ecological types typical of intermediate elevations in the central Great Basin (from Chambers and others 2004b).

An understanding of the factors that differentiate ecological types and of the potential states and transitions within ecological types can be used to design effective strategies for restoring and managing meadow complexes. A model state and transition diagram that illustrates the relationships among the wet, mesic, and dry meadow ecological types and that shows potential alternative states and transitions within each ecological type is shown in fig. 8.7. The diagram illustrates that meadow ecological types occur along water table gradients and are characterized by unique vegetation communities. Abiotic thresholds exist among the different ecological types that are determined by water table depth. Thresholds can be defined based on the parameters that determine the limits of natural variability (Ritter and others 1999) for each ecological type. Threshold crossings occur when a system does not return via natural processes to the original state following disturbance (Laycock 1991; Ritter and others 1999).

Alternative vegetation states within each ecological type typically occur along anthropogenic disturbance gradients (fig. 8.7). Biotic threshold crossings to new alternative states can result from either internal interactions, like competition, or from external factors, like inappropriate livestock use or species invasions. If an ecological threshold to an alternative state has been crossed, management intervention typically is required to return the system to the former state (Wright and Chambers 2002; Chambers and others 2004a). Large changes in either biotic or abiotic conditions and, consequently, ecosystem processes can result in new ecological types with different sets of restoration potentials. For example, a lowering of the water table by as little as 30 cm can result in an abiotic threshold crossing from a wet meadow to a mesic meadow (fig. 8.6).

Use of Vegetation Management

Minor stream incision can result in transitions to drier vegetation communities within meadow ecological types. Management options include stabilizing the stream system and stream banks, as described above, and managing the meadow complex to prevent overgrazing by livestock and invasion of weedy species. Monitoring grazing use, ensuring that utilization guidelines are met, and treating weedy species as soon as they appear can prevent transitions to undesirable states.

Incision that causes a significant drop in the water table may cause all or part of the meadow to transition to a new ecological type with a new site potential. The change in the stream system and groundwater table may occur during one or multiple events. In those cases where it is not ecologically or economically feasible to stabilize the stream system, it may be necessary to wait until the stream has obtained a new base level or is at grade before initiating active vegetation management. In meadows with active springs or seeps that are not adjacent to the stream, portions of the meadow may remain relatively wet.

The first step in determining the potential of a site to support a given ecological type is to monitor the depth to saturation or the water table. This can be accomplished by using soil augers, digging soil pits to evaluate depth to saturation, or installing groundwater wells to measure water table depths. Because water table depths are highly variable both among and within years in mesic, dry, and sage meadow ecological types (Castelli and others 2000; Martin and Chambers 2002), monitoring should be conducted several times during the growing season and for at least two years prior to project initiation (Chambers and others 2004b). The water table depths shown in fig. 8.6 can be used to evaluate site potential. Plant species composition also can be used as an indicator of site potential with the caveat that riparian obligate and facultative species are often long-lived and significant lag times can occur during transition to new ecological states. Establishment and persistence of upland species like the shrubs, big sagebrush (*A. tridentata* ssp. *tridentata*, *A. tridentata* ssp. *vaseyana*), or rabbitbrush (*Chyrsothamnus* species), are strong indicators that site potential has transitioned to sage meadow.

Sites that have maintained their potential to support wet or mesic meadow types may exhibit slight changes in species composition and may only require stabilization of spring channels or stream banks. However, sites that have transitioned rapidly from wet or mesic meadow types to sites with the potential to support dry or sage meadows may exhibit weedy species invasions or undesirable species compositions (Wright and Chambers 2002). Active management that includes prescribed fire to remove upland shrubs and revegetation can be used to improve the ecological condition of these sites and to maintain them as dry or shrub meadows.

The dry meadow type, as originally described, is dominated by grasses and sedges and has relatively shallow water table depths and depths to saturation (-70 to -100 cm in June

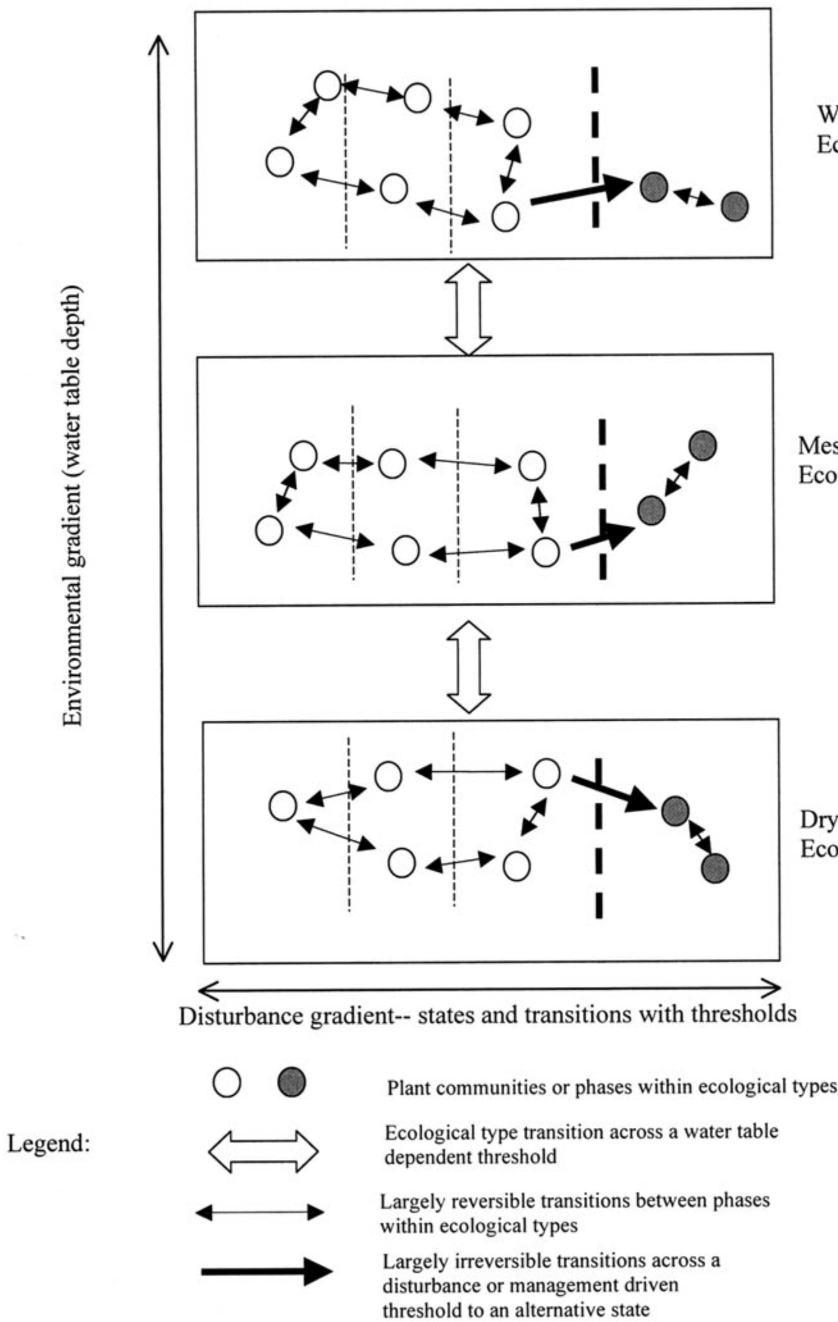

Figure 8.7. Hypothetical state and transition models for the wet, mesic, and dry meadow ecological types. Differences among ecological types are largely dependent on water table depths; differences among states are largely dependent on disturbance and management history (from Chambers and others 2004b).

and July) (Weixelman and others 1996). These water table depths facilitate establishment and persistence of typical dry meadow species such as Nevada bluegrass (*P. secunda* ssp. *juncifolia*). Saturated rooting zones during the spring and early summer prevent establishment and persistence of big sagebrush and other shrubs (Ganskopp 1986). Overgrazing and other perturbations can alter species composition but will not result in shrub encroachment unless the water table drops. Sites with slightly lower water tables (-150 to -250 cm) are characterized by dry meadow species but are susceptible to sagebrush encroachment. Dry meadow species persist because occasional high water tables and favorable environmental conditions facilitate episodic establishment (Chambers and Linnerooth 2001). However, water tables are sufficiently low that basin big sagebrush also can establish and persist (Wright and Chambers 2002). Inappropriate livestock use increases sagebrush establishment by reducing competition from herbaceous species (see Belsky and others 1999). Designation of sites with lower water tables (-150 to -250 cm) as alternative states of the dry meadow ecological type depends on the interpretation of the "range of natural variability" within an ecological type. If the range is considered sufficiently broad to include sites with slightly lower water tables that can exhibit sagebrush encroachment, then these sites represent alternative states of the dry meadow ecological type. Regardless, sites that exhibit sagebrush encroachment but that have typical dry meadow species in the understory can be maintained as dry meadows with prescribed fire and proper livestock grazing (Wright and Chambers 2002).

Sites with deeper water tables (-250 to >-300 cm) are dominated by sagebrush with a minor component of dry meadow species. These sites have crossed abiotic thresholds and no longer have the potential to support the dry meadow ecological type. The failure of typical dry meadow species to establish (Chambers and Linnerooth 2001) indicates that any dry meadow species that occur on the sites are probably remnants of what existed prior to stream incision and lowered water tables. These sites are unstable and can exhibit several different pathways depending on the disturbance regime and initial species composition. In the worst case scenario, they can transition to sagebrush dominance with an understory of upland herbaceous or invasive species. Past research shows that at low to intermediate elevations within the watersheds, basin big sagebrush and Great Basin wildrye can establish on these sites (Wright and Chambers 2002). Thus, the potential exists for at least the more xeric species that characterize the basin big sagebrush/Great Basin wildrye ecological type to also establish (Weixelman and others 1996). Prescribed fire can be used to remove the sagebrush overstory on these sites. Because the herbaceous understory species that characterize the basin big sagebrush/Great Basin wildrye ecological type are almost nonexistent, they must be seeded onto the site. Fire alone can convert these sites to annual forbs and grasses, especially if the fire-adapted, exotic grass cheatgrass (*Bromus tectorum*) or annual mustards exist in the understory (Wright and Chambers 2002).

Methods for successfully revegetating these types of sites can be found in Whisenant (1999) and Monsen and others (2004). Native species that have been successfully established on these sites and that are commercially available include the grasses—Great Basin wildrye (*L. cinereus*), western wheatgrass (*Pascopyrum smithii*), and creeping wildrye (*Elymus triticoides*)—and forbs—yarrow (*Achillia millifolium*) and blue flax (*Linum lewissii*) (Wright and Chambers 2002). Ample sources of sagebrush seeds typically exist adjacent to meadow complexes, and sagebrush usually establishes on its own. If rabbitbrush occurs on the site, it will re-sprout following fire and may preempt the site unless the herbaceous species establish rapidly. Maintenance of these sites requires preventing inappropriate livestock use and invasion of non-native species.

Other Management Considerations

The degree of stream incision and current ecological conditions of meadow complexes in Great Basin watersheds are affected significantly by anthropogenic disturbance. Ongoing studies provide direct evidence that roads have increased the rate and magnitude of stream incision. Several cases of "road captures" have been documented and many others have been observed where streams have been diverted onto road surfaces during high flows (Lahde 2003). These diversions onto road surfaces increase shear stress and stream power and, ultimately, stream incision (Lahde 2003). Once initiated, stream incision can propagate through large portions of the system as a result of knickpoint migration. Active management of roads is needed to minimize the potential for stream diversion onto roads during high flows. This includes minimizing new road crossings and maintaining road conditions that decrease the likelihood of avulsion and stream diversion during high flows. It also includes long-term management that is aimed at relocating existing roads and positioning new roads out of the valley bottoms.

Inappropriate livestock use and other types of disturbance like off-road vehicle use and camping activities can alter physiolological responses and competitive interactions of meadow species (Martin and Chambers 2001a, 2002) and, thus, community composition and ecological condition of meadow ecological types (Martin and Chambers 2001b). These disturbances can increase the effects of changes in water tables resulting from stream incision. For example, inappropriate livestock use (timing, season, or duration) of riparian meadows often compacts soils and decreases infiltration capacity (Weixelman and others 1997) and alters plant physiological processes and population and community dynamics through vegetation removal and nitrogen deposition (Martin and Chambers 2001a, 2001b). Inappropriate livestock use also can decrease stream channel stability by removing stream bank vegetation, decreasing bank undercuts, and increasing bank erosion (NRC 2002). Informal fall monitoring of several riparian meadows in the central Great Basin by Chambers over multiple years indicated that repeated overuse by livestock (60 to 80% utilization) likely affects streambank stability and ecological conditions in many of these meadows. Proactive management of livestock use and other anthropogenic disturbances is essential to maintain and improve the ecological conditions of these meadows and to ensure that stream stabilization and vegetation management projects succeed.

Post-Project Evaluation, Monitoring and Adaptive Management

Until recently, evaluations, or post-project appraisals (PPA), of most stream and meadow restoration/stabilization projects were limited to qualitative assessments, if they were conducted at all. The potential benefits of such appraisals have received considerable attention in recent years, and it is apparent that PPAs are essential for developing sound management strategies. Several advantages exist for systematically collecting post-project data for stream stabilization/restoration projects (Downs and Kondolf 2002) that are applicable to meadow complexes in the central Great Basin. These advantages are: determining (1) if the treatment was carried out or constructed as originally planned; (2) whether the treatment accomplished the project's objectives or success criteria; (3) if the project resulted in unexpected, negative effects; (4) if the project could be altered to improve future treatments; and (5) whether the treatment proved to be an effective use of limited resources.

It is important to note that the development of a PPA does not start after the project has been implemented. Rather, it begins at the onset of the project with the creation of one or more explicit statements that define success criteria. As previously stated, success criteria are quantitative objectives against which post-project data can be compared to evaluate the performance of a specific approach. A PPA also requires collection of pre-project baseline data and post-project monitoring data, which can be compared to quantitatively determine how a system changes through time.

Many investigators and land managers now argue that PPAs should be combined with an adaptive management strategy (Walters 1986, 1997; Downs and Kondolf 2002). Halbert and Lee (1991) define adaptive management as an approach that:

> …treats management programs as experiments. Rather than assuming that we understand the system that we are attempting to manage, adaptive management allows management to proceed in the face of uncertainty. Adaptive management uses each step of a management program as an information-gathering exercise whose results are then used to modify or design the next state in the management program.

Adaptive management is not the same as management by trial and error. Rather, adaptive management involves systematic collection and analysis of data through sound ecosystem monitoring and subsequent revision of a management approach on the basis of the collected scientific information. The primary advantage of this approach is that it allows management decisions to be revised as new information is obtained on how the system functions (Wieringa and Morton 1996).

It may not seem necessary to expend the time and effort to develop detailed design criteria and post-project appraisals for relatively small meadow treatments. However, given the importance of meadow ecosystems to the region and the limited quantitative data regarding the performance of meadow treatments, we believe that PPAs coupled with adaptive management strategies should be used in the Great Basin.

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