Applying Keyline Design Principles to Slope Wetland Restoration in a Headwater Ecosystem

November 2019

Funds to create this Technical Guide were provided by the Environmental Protection Agency, Region 6 under Section 104(b)(3) of the Clean Water Act, awarded to the New Mexico Environment Department Surface Water Quality Bureau Wetlands Program.

Citation:

Walton, M., J. W. Jansens, J. Adams, M. Tatro, T. E. Gadzia and F. E. Sawyer, 2019. Applying Keyline Design Principles to Slope Wetland Restoration in a Headwater Ecosystem. New Mexico Environment Department, Surface Water Quality Bureau Wetlands Program (NMED-SWQB), Santa Fe, New Mexico. 41 p.

Cover:

Slope Wetland Restoration West Holman Creek Site, Comanche Creek Watershed, Carson National Forest, New Mexico, by Mollie Walton, Quivira Coalition, June 2018.

Applying Keyline Design Principles to Slope Wetland Restoration in a Headwater Ecosystem

November 2019

Quivira Coalition
1413 Second Street, Suite 1
Santa Fe, NM 87505
(505) 820-2544
www.quiviracoalition.org

Ecotone Landscape Planning, LLC
1413 Second Street, Suite 5
Santa Fe, NM 87505
(505) 470-2531
www.ecotonelandscapeplanning.com

TerraSophia, LLC
PO Box 571
Moab, UT 84532
(415) 306-6618
www.terrasophia.com

New Mexico Environment Department
Surface Water Quality Bureau (NMED-SWQB), Wetlands Program
F. Emile Sawyer, Wetlands Program Project Officer
P.O. BOX 5469
Santa Fe, NM, 87502
(505) 827-0187
www.nmenv.state.nm.us/swqb/wps/#Wetlands

Graphics Concepts
Jeffrey Adams, Jan-Willem Jansens, and Mollie Walton

Layout and Design
Tamara Gadzia

Content Reviewers
Margie Tatro, Maryann McGraw, and F. Emile Sawyer

This document can be downloaded as a PDF from the following link:
www.env.nm.gov/surface-water-quality/wetlands.

Table of Contents

Page

Table of Contents, cont.

Page

ACKNOWLEDGMENTS

Almost all of the restoration work done in the Comanche Creek Watershed by the Quivira Coalition, associated restoration contractors, and volunteers has been funded by grants contracted through the New Mexico Environment Department (NMED), Surface Water Quality Bureau (SWQB). Special thanks are due for the staff at the NMED SWQB Wetlands Program. Maryann McGraw, Karen Menetrey, and Emile Sawyer have all made significant contributions to this project.

The restoration specialists who lent their existing knowledge and willingness to think innovatively to the project include Jan-Willem Jansens, Jeffrey Adams, Mark Reineke, Margie Tatro, and Bill Zeedyk. Craig Sponholtz originated the idea to explore Keyline Design application in the wetlands of the Comanche Creek Watershed.

The work on the ground could not have been completed without the support of the dedicated Forest Service employees entrusted with management of our public lands. Greg Miller, Jack Lewis, John Littlefield, Ezequiel Rael, and Michael Gatlin of the Carson National Forest have been wonderful project partners. Michael Gatlin was the project liaison and an exceptional professional.

The Comanche Creek Working Group serves as the watershed stakeholder alliance and provides a framework for forward thinking about restoration, multiple land uses, and good collaboration. The Valle Vidal Grazing Association and Mark Torres, in particular, have been very good partners in collaborative land management.

In completing this guide, Tamara Gadzia, Kathyrn Brewer, and Dorothy Williams have been instrumental. Their expertise is particularly appreciated for improving the quality of the presentation of this technical guide.

Numerous volunteers come to work each summer to learn new techniques and ensure that water keeps moving through the mountain wetlands. Inspiration always flows from people who are dedicated to making a difference. These volunteers are the backbone of every project.

INTRODUCTION

An interest in developing, testing, and documenting innovative approaches to slope wetland restoration has driven many projects funded by the New Mexico Environment Department (NMED) Surface Water Quality Bureau (SWQB) Wetlands Program. A project funded by the NMED SWQB Wetlands Program to test the application of Keyline Design principals in slope wetland restoration was completed by the Quivira Coalition and associated restoration professionals.

Quivira and the Comanche Creek Working Group have worked together to improve wetland and riparian conditions in the Comanche Creek Watershed on the Valle Vidal District of Carson National Forest since 2001. Through these efforts, the Comanche Creek Watershed has been used as a testing ground for innovative restoration concepts. Quivira's role evolved as the organizer for the restoration work, which has included securing funding through grant writing, serving as a project manager for several large-scale restoration projects, and conducting volunteer work weekends.

Each summer, volunteers camped at 10,000 feet above sea level to build restoration treatments that result in the slow and steady stabilization of degraded wetlands and streams. Volunteer efforts provided an in-kind match for the grant-funded contract work of restoration professionals. Contractors have been able to use the opportunities provided by Quivira and NMED to test new treatment concepts and gain cumulative experience in the application of varied restoration techniques.

Many restoration professionals have contributed to the conceptual toolbox for stabilization and restoration in the Comanche Creek Watershed. This guide builds upon information and innovation presented in the technical guide, *Restoration of Slope Wetlands in New Mexico: A Guide for Understanding Slope Wetlands, Causes of Degradation and Treatment Options* (2014) by reporting on the testing of traditional Keyline Design concepts. Although developed for agricultural application, Keyline Design can be modified and used effectively for wetland restoration to spread water to dewatered slopes and diminished wetlands.

The above photo shows a log mat flow splitter (center) constructed to intercept channelized flow and convert it to sheetflow which will be intercepted by vegetation in the exclosure (fencing top left). Keyline Design principles lend themselves to linked treatment structures to maximize water spreading and harvesting benefits.

A team of restoration professionals identified locations in the Holman Creek Wetland Complex within the Comanche Creek Watershed, where Keyline Design principles and water spreading techniques, used in conjunction with Natural Channel Design (Rosgen, 2011), could potentially expand wetland extent. The Holman Creek Wetland Complex has four first-order tributaries that flow into Holman Creek before it meets the Comanche Creek main stem. Each first-order tributary has a set of unique attributes that make the entire Complex ideal for testing innovative restoration techniques. Redistribution of water is the ultimate goal of applying Keyline Design principles in the restoration of slope wetlands.

The hydrology of the slope wetlands in the Holman Creek Wetland Complex is characterized by groundwater and surface flows, which both predominantly originate from snowmelt in headwater ecosystems. Slope wetlands with snowmelt as their primary water source have a longer period of water distribution and infiltration than systems that are proportionally more dependent on summer storm events. In these slope wetland systems where degradation has occurred, restoration techniques should be designed to increase both surface and subsurface flows. Addressing the root cause of the degradation (interrupted hydrology) will improve wetland ecological functions and build their resiliency to climate change and other human and natural stressors.

This technical guide aims to inform wetland restoration program managers, restoration professionals, contractors, volunteers, and students, about the specific role Keyline Design can play in slope wetland restoration. The innovative approach to wetland restoration offered by Keyline Design, integrates and follows years of technical development, testing, and documentation of a large toolbox of techniques for wetland restoration. The first Chapter of the guide provides an overview of Keyline Design principles to set the stage for the adaptation of many of these principles for slope wetland restoration. Chapter 2 provides a brief review of the basics of headwater slope wetlands and the stressors that have resulted in diminished ecological function. Chapter 3 provides an overview of ways of reading the landscape using the Keyline Scale of Permanence and identifying *keypoints* in the landscape. Chapter 4 details specific techniques tested in the Holman Creek Wetland Complex. Chapter 5 summarizes the project and provides suggestions for future work using the Keyline Design principles for slope wetland restoration.

CHAPTER 1 - **KEYLINE DESIGN**

KEYLINE DESIGN FOR IMPROVING DRYLAND AGRICULTURAL PRODUCTION

The Keyline Design concept was developed in the mid-twentieth century by Australian mine engineer and ranch owner P. A. Yeomans. He developed the Keyline method as a comprehensive design strategy for enhancing agricultural land productivity (Yeomans, 2002). ("Keyline" is a registered trademark. "Keyline Designs" is a registered business name of Ken B. Yeomans.)

Water flow patterns are determined by gravity and landscape conditions, which cause water to take the shortest route down a hillside. Landscape conditions can be modified to alter flow patterns in order to lengthen water routes and increase water resource benefits. These are the primary goals of Keyline Design concepts.

Keyline Design may be implemented using a range of techniques, including a series of water holding ponds high on the landscape, swales and berms, tree and shrub hedgerows, and use of the keyline plow as a subsoiler (Fig. 1.1). Each of these lengthen water flow paths to prolong water residence time over and through the landscape.

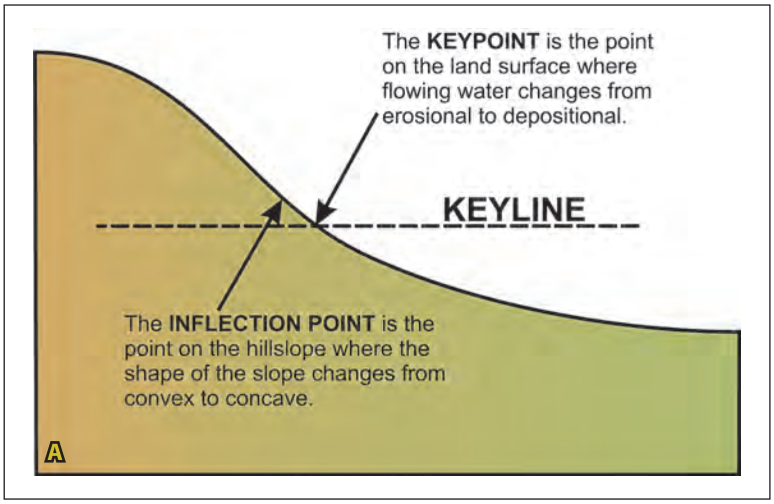
©Google Earth® and Taranaki Farms, Woodsend, Australia, 2019

Photo insert ©Taranaki Farms, Facebook accessed, 2019

Figure 1.1A. Google Earth overview image of Taranaki Farm in southern Australia. Figure 1.1B. Insert shows landscape view of Keyline Design techniques at Taranaki Farm. Keyline Design concepts may be integrated over large acreages, as shown in these examples above.

KEYLINE DESIGN CONCEPTS

Keyline Design is a planning and design approach for landscape modification that revolves around the concept of an important location in the landscape called a *keypoint*. Once a keypoint is located, a *keyline* can be determined to create a keyline patterning to guide water across the topography of a landscape (Fig. 1.2).



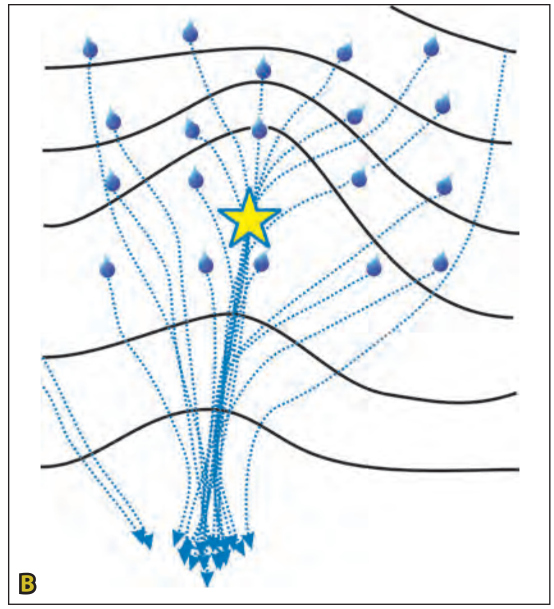


Figure 1.2A. Cross-sectional view shows the inflection point, keypoint, and keyline. Figure 1.2B. A map view of a hillslope with topographic lines shows the location of the keypoint (yellow star) and potential water storage points as blue water droplets.

Keyline terminology is fairly simple. The *inflection point* is the point on the hillslope where the shape of the slope changes from convex to concave. The *keypoint* is the point on the land surface where flowing water changes from erosional to depositional. It is the highest point on the landscape where water can be held. Vegetation and soil type also influence patterns of erosion and deposition, which can influence the location of the keypoint.

The *keyline* (yellow line in Fig. 1.3) of the primary valley is a near contour line extending from the keypoint in both directions (Yeomans, 2002). The keyline plow furrows follow a slightly off-contour pattern, parting from the keyline. Keyline Design assists water flow across a landscape by creating pathways for water to cross the drier portions of the landscape and remain longer in the local ecosystem. Increased water residence time prolongs water availability for uptake by living organisms.

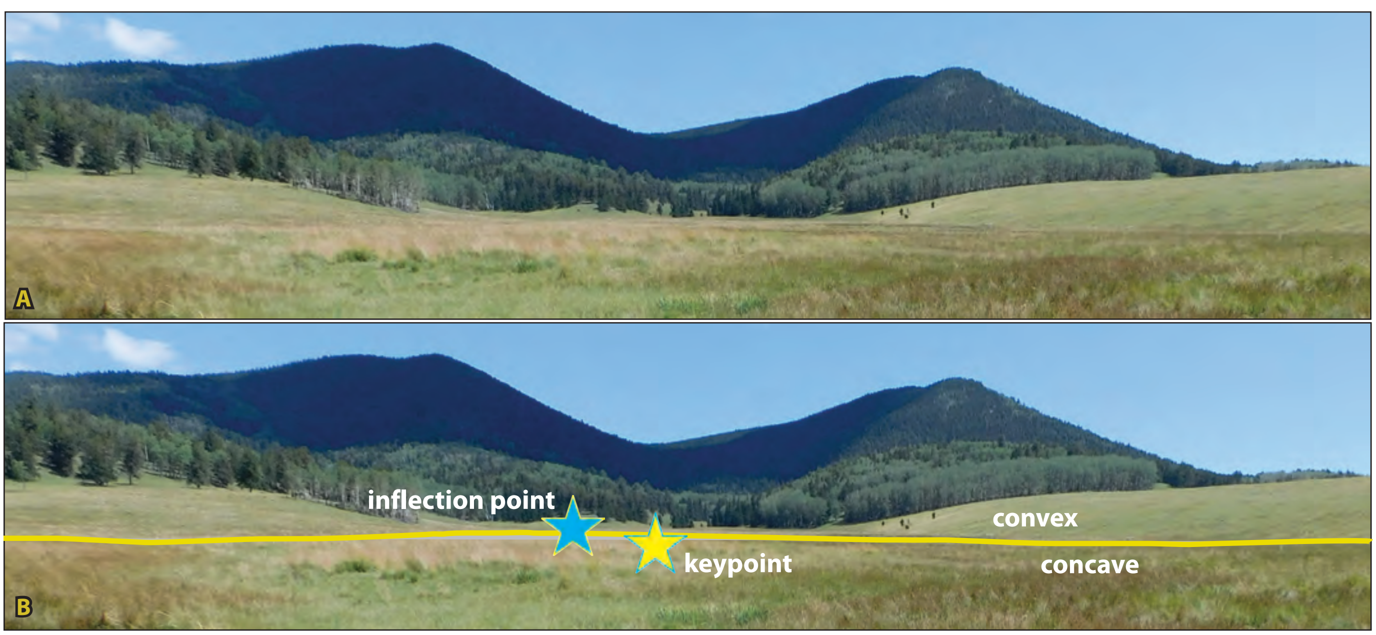


Figure 1.3A. A photo of Grassy Creek, Comanche Creek Watershed, looking upvalley towards the keypoint. Figure 1.3B shows the same photo with the inflection point (blue star) and the keypoint (yellow star) locations. At the keypoint, flowing water ceases to erode the land surface and begins to deposit sediment. The yellow line is an approximate keyline location.

The *keyline pattern* is created by sequences of Keyline Design structures placed in precisely selected locations on the landscape. These structures work in concert to bring about desired outcomes. Figure 1.4 shows four Keyline Design techniques in use on the Taranaki Farms property in southern Australia.

Figure 1.4. An aerial view of Taranaki Farms showing examples of Keyline Design techniques as labeled on the landscape: hedgerows, keyline plow patterns, ponds high on the landscape, swales and berms.

KEYLINE STRUCTURES

A *keyline pattern* can be implemented using a range of techniques, including placing ponds high on the landscape, constructing swales and berms, planting tree and shrub hedgerows, and application of the keyline plow subsoiler.

Ponds Placed at Higher Elevations on the Landscape

An important concept in traditional Keyline Design is to construct ponds high in valleys to hold water at the highest possible keypoint on the landscape (Fig. 1.5). Water held first at this keypoint can be redistributed for greater effect using Keyline Design structures and off-contour drainage distribution patterns, such as swales and berms, which hold and slowly release water for redistribution and infiltration.

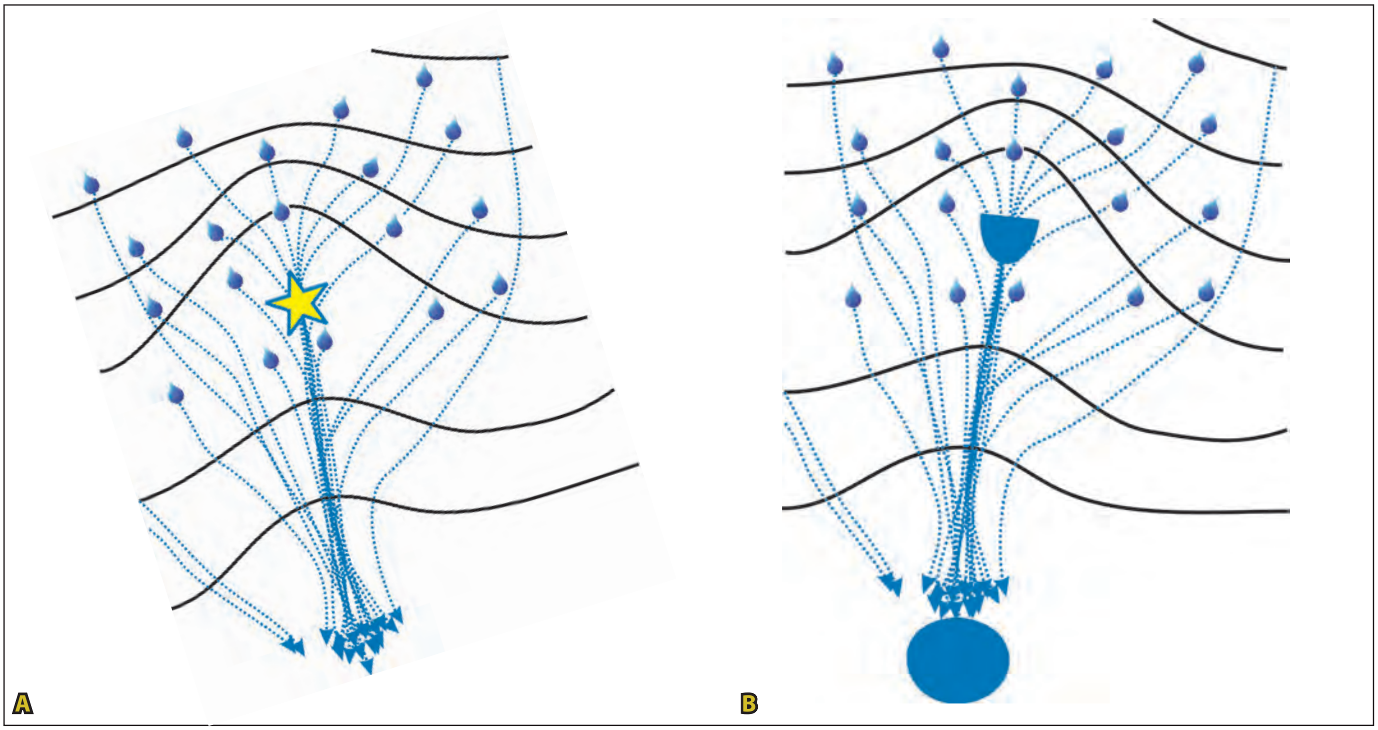


Figure 1.5A. Water flows down hillslopes and becomes concentrated in the valley. The yellow star shows the keypoint where water can be held highest in the landscape. Black lines in the diagrams are topographic contour lines. Figure 1.5B. By ponding and allowing water to infiltrate at the keypoint (half circle), water is collected before it has a chance to accelerate down the main valley channel to a traditional pond location (large circle). Stored water can be redistributed through other *keyline structures* to drier parts of the landscape.

Swales and Berms

Swales are nearly level, wide, and shallow strips that have been dug below surface level to accumulate water and let it slowly infiltrate into the soil or to spread it from one end of the swale to another. In some circumstances, a berm is needed to hold water in the swale for channelling to a desired location. A *berm* is a mound of soil formed when digging a swale. Excavated soil is placed on the downslope edge to retain surface runoff, increase water infiltration, and potentially direct surface water to a drier location (Fig. 1.6).

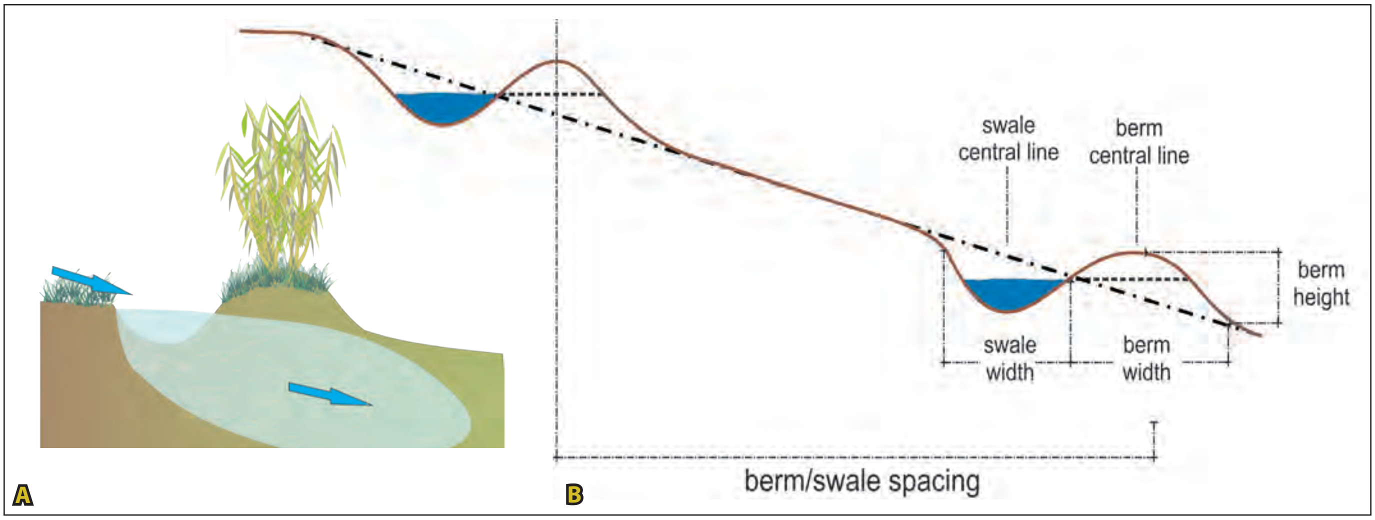


Figure 1.6A. This graphic shows water in a swale infiltrating below a berm. Swales and berms are constructed on hillslopes to retain water and/or deliver water to a water-spreading structure in order to increase infiltration and plant production. Blue arrows indicate flow direction. Figure 1.6B illustrates the concept of proper swale and berm placement on the landscape.

Hedgerows

Often a *hedgerow*, a row of shrubs or trees, is used in conjunction with a swale and berm. Hedgerows can slow erosion and allow water to infiltrate into the landscape. Trees or shrubs are planted on the berm and sometimes in the swale to take advantage of the higher soil moisture for growth and production. Once established, a dense row of woody vegetation can serve the same function as a swale and berm system. Its root system helps improve soil structure, water-holding capacity, and infiltration. Figure 1.7 shows a hedgerow on the downslope side of a swale and berm.

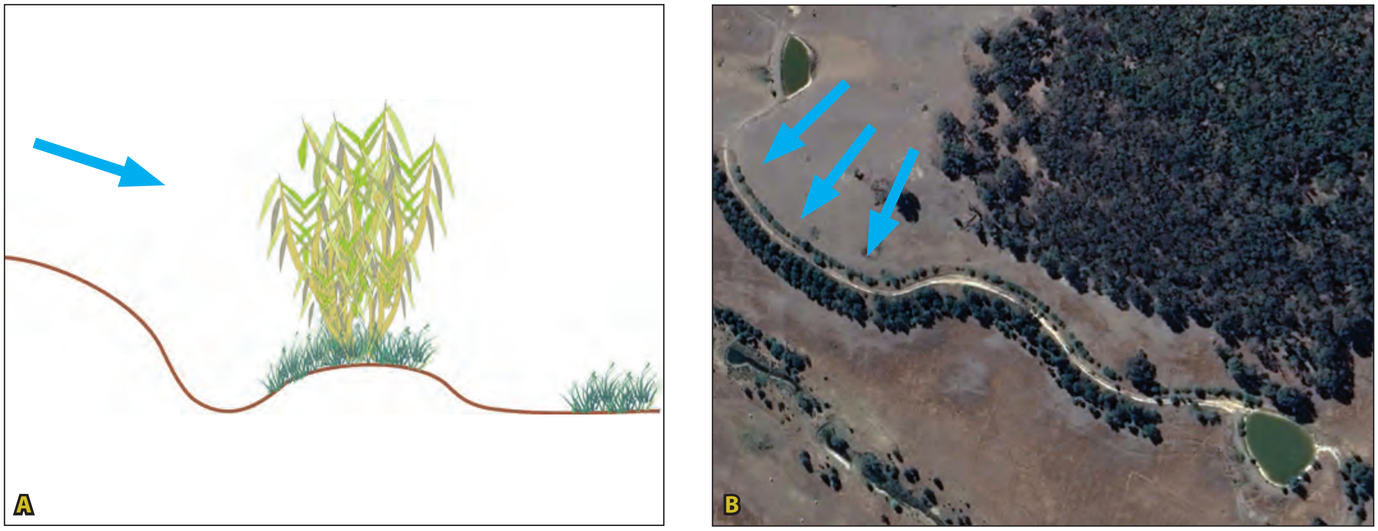
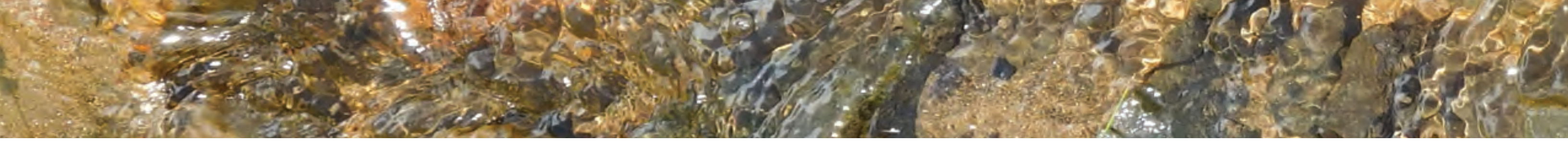


Figure 1.7A. Cross-section graphic shows a swale and berm with a hedgerow planted on the berm. Figure 1.7B. An aerial view of a dense hedgerow in conjunction with an on-contour swale and berm is shown at Taranaki Farm. Blue arrows show the direction of water flow down the hillside.

Keyline Plow Subsoiler

Another tool for implementing keyline patterning is the keyline plow, which is designed as a subsoiler to deeply penetrate the soil without inverting or mixing it (Fig. 1.8). A plow rips the ground, creating micro-ditches which harvest and divert the water. The ground surface is slightly raised from the plow line, which acts as a very small berm. The narrow trenches move water from wetter to drier parts of the landscape. The keyline plow is often used where there is a compacted layer beneath the soil surface. A keyline plow was not used in this project for reasons discussed in Chapter 4.

Figure 1.8A. The keyline plow uses a shank (yellow arrow) which creates space in the subsoil (Figure 1.8B). Figure 1.8C. The keyline plow is used in Keyline Design to make parallel furrows without inverting the soil surface, as shown in the photograph.



INTRODUCTION TO THE KEYLINE SCALE OF PERMANENCE HIERARCHY FOR PLANNING

A Keyline Design can be fairly simple or extremely complex, depending on landscape conditions, scale, project goals and constraints. To address the complexity of this kind of landscape modification, Yeomans created a hierarchy for planning decisions called the Keyline Scale of Permanence (Fig. 1.9).

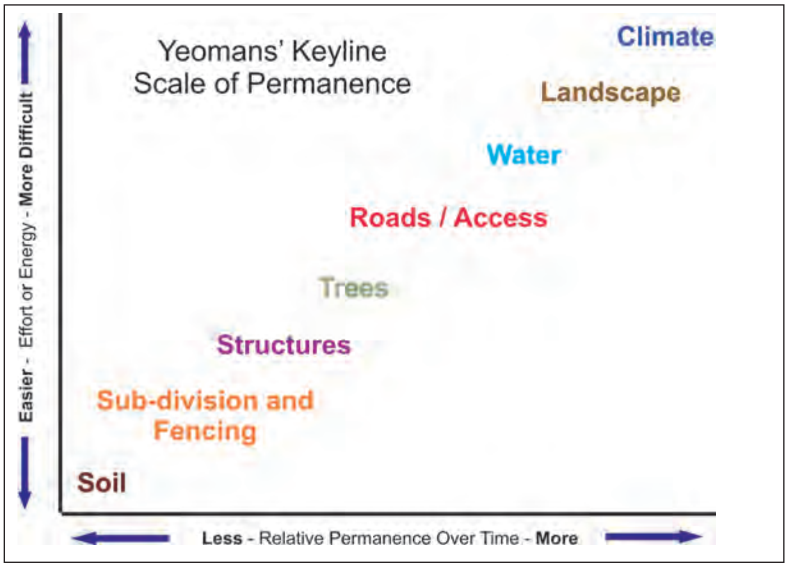
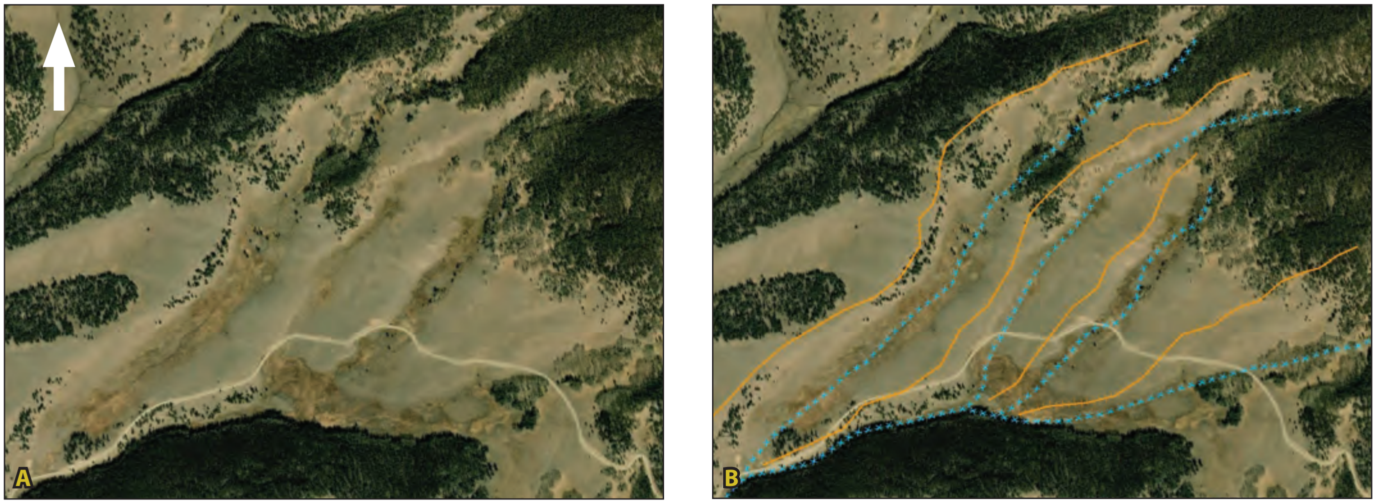


Figure 1.9. This graph of Yeomans' Keyline Scale of Permanence shows landscape variables that require the least energy (bottom left) to create positive changes to those that require the most energy and time (top right).

Using the Keyline Scale of Permanence hierarchy, a systematic assessment of water-harvesting and water-spreading opportunities ideally starts at the top of the valley with the most water (the priority valley). This valley has the most potential to yield positive results from manipulating water flow and infiltration (Fig. 1.10).

The priority valley has the greatest flow and most significant acreage (the western tributary in this example). Valleys with smaller acreages and fewer water sources have lower priority. A more detailed discussion of the planning hierarchy as adapted for slope wetland restoration is provided in Chapter 3.



©Esri, World Imagery

Figure 1.10A. In this aerial view of the Holman Creek Wetland Complex (bisected by Forest Service Road 1950), the white arrow points north. Figure 1.10B. Overlay on the same image of approximate ridge lines (orange) and wetland valley thalwegs (blue lines).

Keyline Design, as originally intended for dryland agricultural production, includes many concepts that can be adapted for slope wetland restoration. However, there are also many that do not apply quite as well. Slope wetland restoration on the project site in the Comanche Creek Watershed adapted certain keyline techniques that harvest, retain, spread, and infiltrate water. Other traditional keyline designs for dryland agriculture have a large infrastructure footprint requiring extensive land disturbance and continued maintenance. These techniques were not deemed appropriate for natural ecosystems on public lands such as the Comanche Creek Watershed.

CHAPTER 2 - **ADAPTING KEYLINE DESIGN FOR SLOPE WETLAND RESTORATION**

LAND USE IMPACTS IN DEGRADED SLOPE WETLANDS

An important aspect of restoring the function to degraded landscapes is understanding the stressors that have triggered the decline in function. This first step in identifying stressors for stabilization and restoration design is missing from Yeomans' Keyline Scale of Permanence design hierarchy. Stressors have been added to an adapted version of the hierarchy, which is presented under Land Use in Chapter 3.

Restoring dispersed flow pathways (surface and subsurface) in degraded slope wetlands is essential for maximizing soil water saturation throughout an entire historical wetland landscape. Slope wetlands are through-flow wetlands (Brinson, 1993 and 2008) (Fig. 2.1).

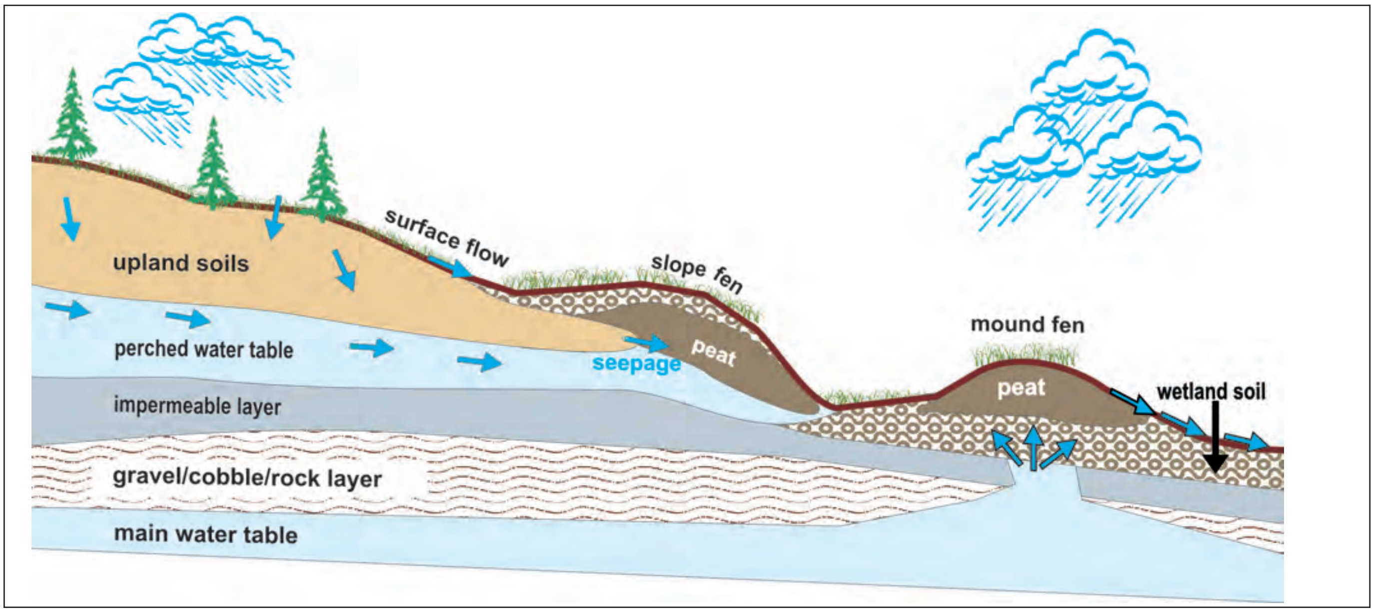
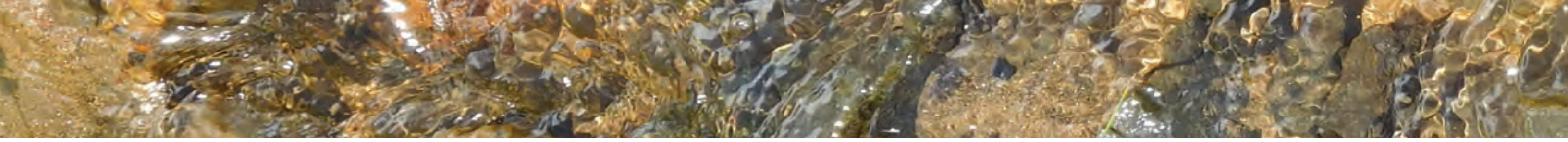


Figure 2.1. Precipitation infiltrates into the soil and also runs over the soil surface. In slope wetlands, surface runoff is augmented by groundwater emerging from springs and spring seeps at the surface. Blue arrows show flow paths.

Degraded slope wetlands can behave more like riverine wetlands with concentrated water flow. Restoration of slope wetlands must include dispersing concentrated flow paths to recharge wetland soils (both surface and subsurface flows). Under specific conditions, applying Keyline Design principles for this purpose adds value to existing wetland restoration methods.

Slope wetlands in the Comanche Creek Watershed have degraded over time due to a variety of land use impacts (legacy stressors) that have been discussed in detail in a previous technical guide, *Restoration of Slope Wetlands in New Mexico: A Guide for Understanding Slope Wetlands, Causes of Degradation and Treatment Options* (2014).

Legacy stressors such as mining, logging, poor road infrastructure, and overgrazing lead to degradation in headwater systems. Ongoing stressors, such as climate change impacts and animal trailing, exacerbate existing degradation. The steepness of mountain slopes and the removal of vegetation causes erosional processes to accelerate, leaving bare soil vulnerable to the actions of wind and water. Often erosion in these steep landscapes starts when water is captured by a road or trail that concentrates water flow in a channel.



SYMPTOMS OF DEGRADATION IN SLOPE WETLANDS

The removal of vegetative cover to create a road or trail exposes soil to compaction and accelerates soil erosion and surface runoff. Erosional *nick points* (initial point where erosion occurs) originate where vegetation is removed and soil loss is accelerated. The eroded surface is often lower than adjacent vegetated surfaces, capturing water flow. The concentrated flow accelerates soil loss and a headcut forms at the point where the soil's capacity to withstand erosive forces fails. Through this process, trails and roads create nick points that lead to headcuts, resulting in down-cutting channels throughout the wetland (Fig. 2.2). Soil type, soil compaction, and soil particle size influence both susceptibility to *nicking* and the rate at which headcuts erode.

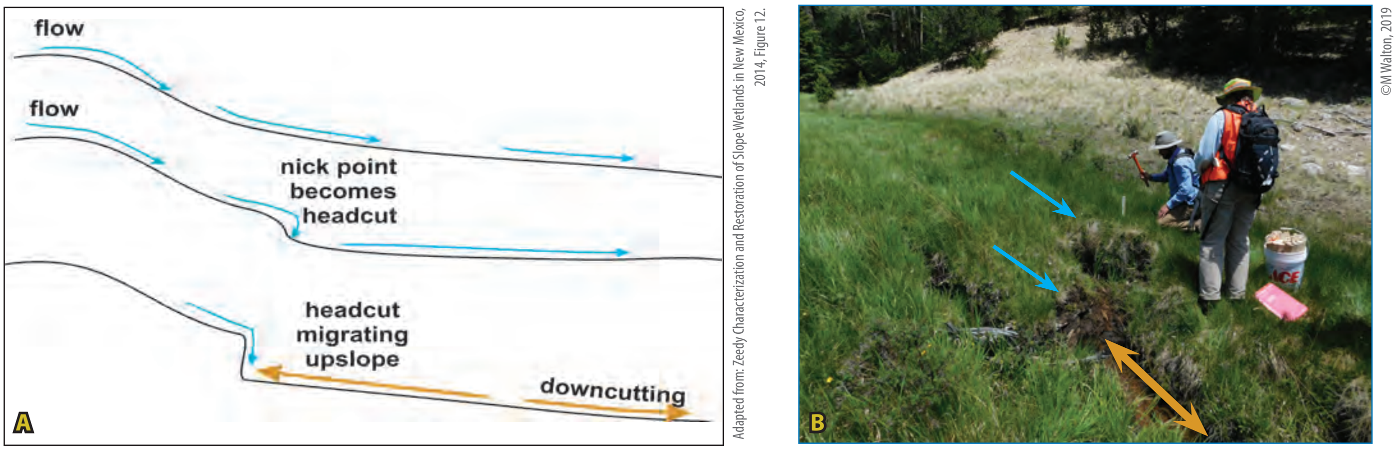


Figure 2.2A. Nick points often turn into headcuts in valley bottoms. Headcuts always migrate upslope and lead to channel downcutting (orange arrows). Figure 2.2B. In the photograph, blue arrows show water flow paths with arrow points at headcuts. The orange arrow indicates the migration of headcut upslope and channel downcutting below.

A *headcut* in a slope wetland is an abrupt drop in elevation caused by concentrated water flow cutting through intact wetland vegetation. The process of erosion is accelerated as the headcut becomes larger. Larger drops in elevation at the headcut cause water to rush more quickly over the bare soil surface. The headcut migrates upslope, and the channel below downcuts. As the channel cuts further into the wetland soil, surface flow is increasingly concentrated and shallow ground water is drained, drying out the wetland landscape. If unchecked, these processes of slope wetland erosion lead to extensive degradation over time and may even result in total loss of wetlands and ecological function (Fig. 2.3).

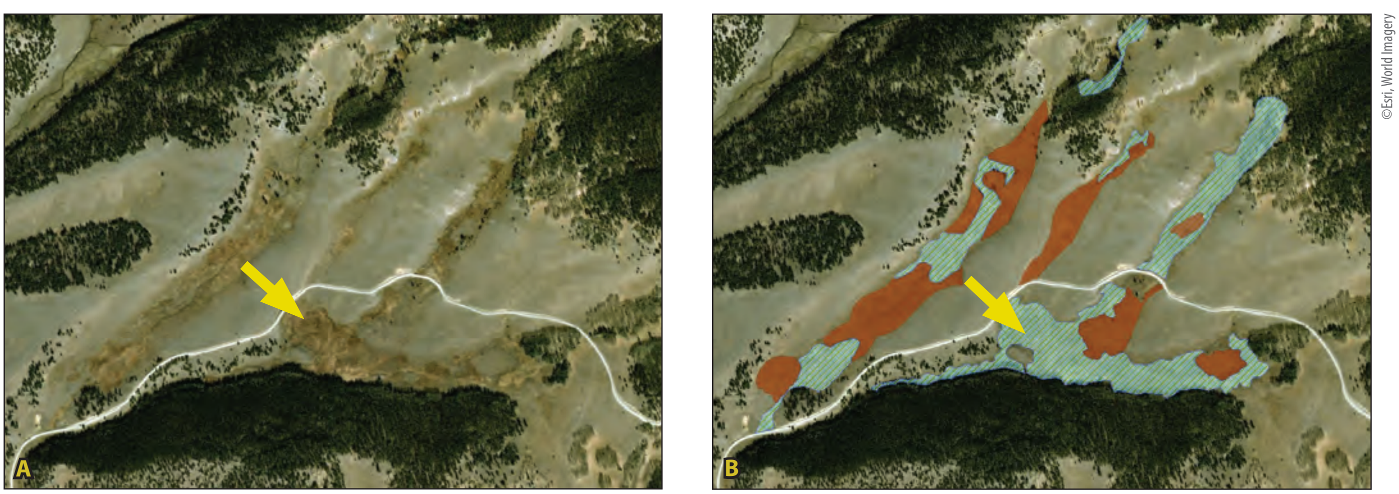


Figure 2.3A. Brighter areas in the primary valleys show existing wetlands (yellow arrow points to some wetland vegetation). Figure 2.3B. Wetlands are shown in green and blue hatch. These areas still support obligate wetland vegetation. The burnt orange color indicates places where wetlands have dried, becoming wet meadow and in some areas have completely transitioned to dryland vegetation.

Typically, the channel that forms in a slope wetland concentrates flow on one side of the valley or the other. This results in large areas that become drier over time. The application of Keyline Design in headwater slope wetland systems focuses not on the hillslopes, but on changing the water flow patterns and aggrading (raising the grade of) incised channels to rewet the dried slope wetlands in the valley bottoms. Distinct areas of functioning slope wetlands interspersed with drying and desiccated wetlands provided a good template for testing Keyline Design principles in the Holman Creek Wetlands Complex within the Comanche Creek Watershed (Fig. 2.4).

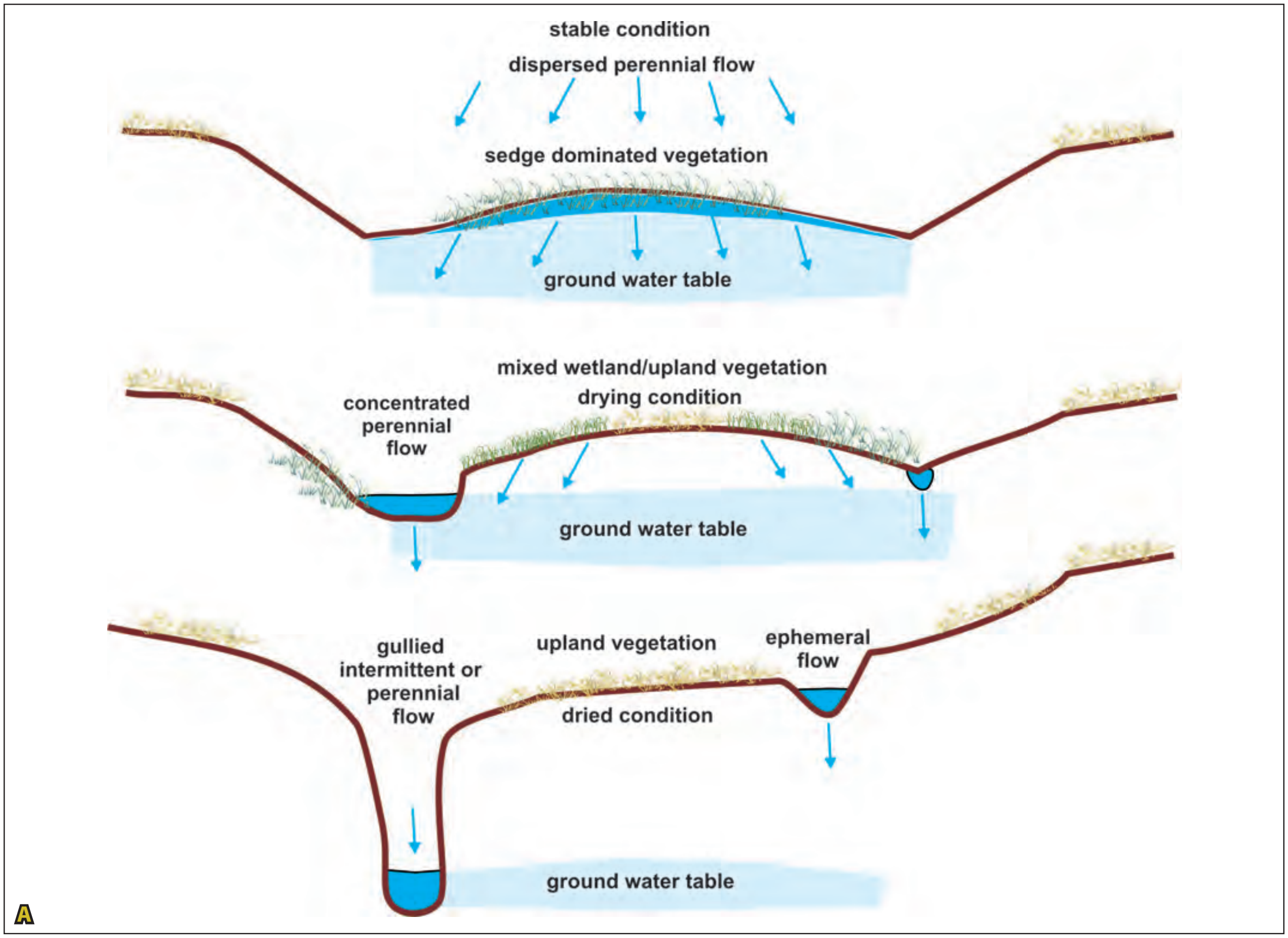


Figure 2.4A. Evolution of slope wetland degradation shows subsurface flow and dispersed perennial surface flow are captured and concentrated by a downcut channel on the side of the valley, leaving patches of drying wetland in an elevated position above the water table.

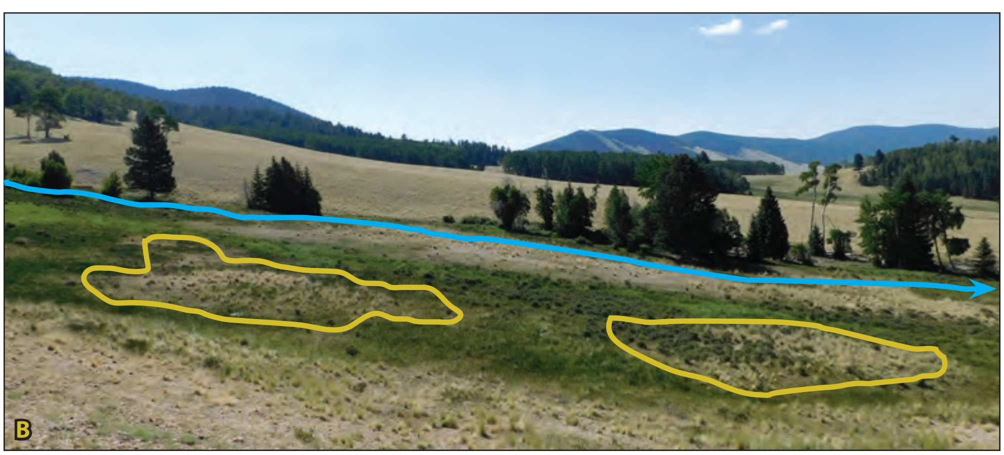
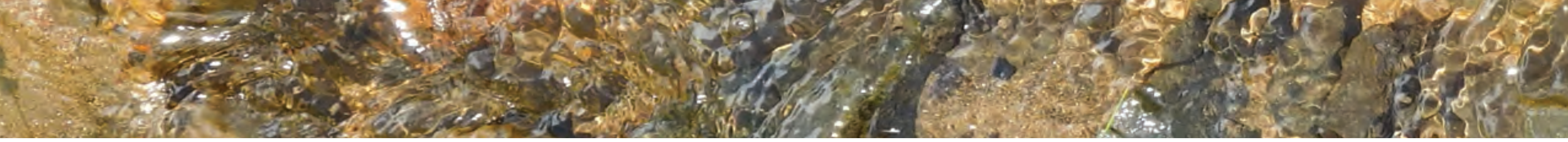


Figure 2.4B. A downcut channel on the side of a valley in the Holman Creek Watershed (blue line) has resulted in extensive patches of drying wetland (yellow polygons).



In degraded slope wetland systems in the Comanche Creek Watershed, many wetland areas have channelized flows of concentrated water moving fast through the system without inundating or saturating the floodplain. Wetland valley soils are bypassed by surface flows needed to replenish them.

In Figure 2.5, the bright green vegetation on valley left is a drying fen, while the bright green lower in valley right is wetland dominated by *Carex* species (sedge). The dark green vegetation is *Juncus* species (rush); its presence indicates that the soil has lost too much water storage to support obligate wetland vegetation but has not yet dried enough to transition to upland vegetation. The presence of *Juncus* species indicates that there may still be time to restore the hydrological function and return the area to slope wetland.

Figure 2.5. Looking downvalley in West Holman Creek, the channel has been captured on valley right, which has caused the drying of fens and wetlands on valley left (blue line indicated location of captured channel and direction of flow).

For the purpose of slope wetland monitoring after restoration treatments, the edge of the extent of obligate wetland vegetation is referred to as the *wetland greenline (Winward, 2000)*. The location of the wetland greenline allows restoration practitioners to identify the extent of functioning wetland plants and soils (Fig. 2.6).

Figure 2.6. Bright green vegetation in the photo above suggests where greater amounts of water storage occur near the surface in the wetland soils, which act as underground reservoirs that support the ecosystem.

The deep green vegetation indicates locations where water is concentrated in the valley soils, especially obvious in drought years. The photograph in Figure 2.6 was taken was in 2018, a year of exceptional drought in the Comanche Creek Watershed. Though the hillslopes are dry, the wetland soils in the valley bottom have stored enough water to maintain vegetation growth in a drought year.

The vegetation distribution relative to the wetland greenline tells the story of where and how much water is stored in the valley soils (Figures 2.6 and 2.7) providing clues to the sources of water in the headwater system. Wetland vegetation can indicate locations where groundwater upwells to the surface in the absence of sheetflow.

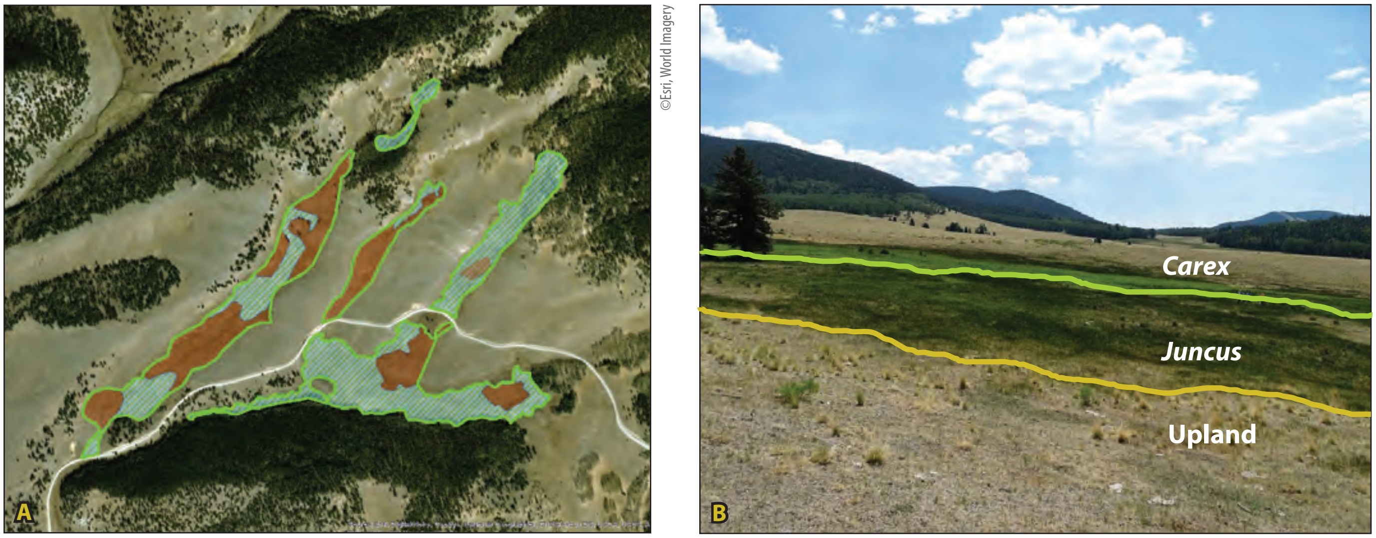


Figure 2.7A. The green line around the primary valleys in the aerial photograph shows the theoretical potential extent (the maximum possible wetland greenline) of slope wetland vegetation and burnt orange areas indicate drying or dried wetlands. Figure 2.7B. The *Carex* (sedge) wetland greenline is shown as a bright green line and the *Juncus* (rush) wetland greenline is yellow.

Through degradation, wetland extents have diminished as water takes a faster flow path down the valley, leaving areas of former wetland to transform into wet meadows and sometimes islands of upland grasses within the former slope wetland complex (Fig. 2.8).

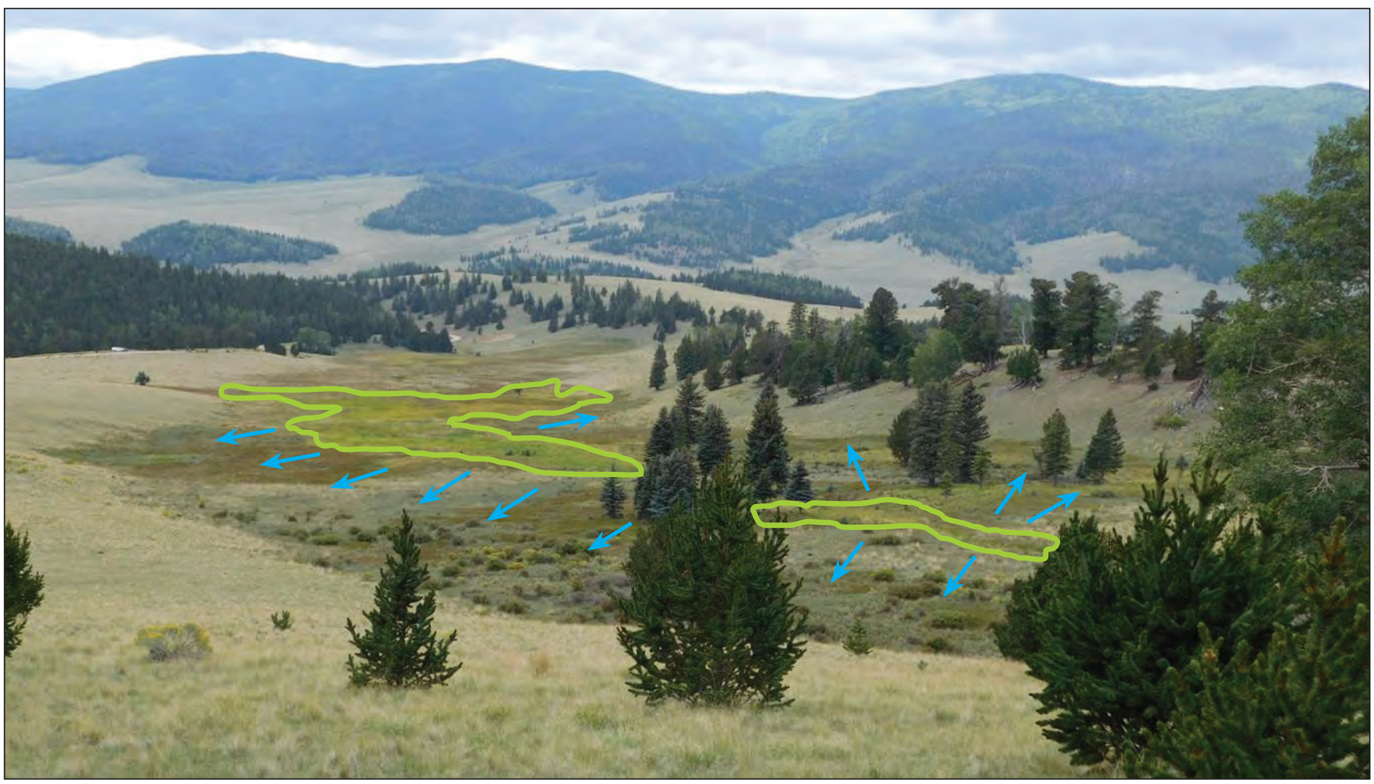
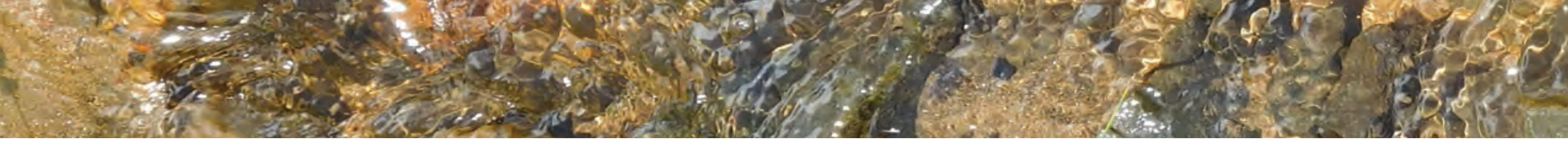


Figure 2.8. Looking downvalley in West Holman Creek, the bright green polygons show the extent of wetland vegetation species indicating ground water is still near the surface in the center of the valley. The blue arrows point to areas where water could be redistributed to restore desiccated wetlands. Restoration activities focus on dispersing water towards the drying wetlands.

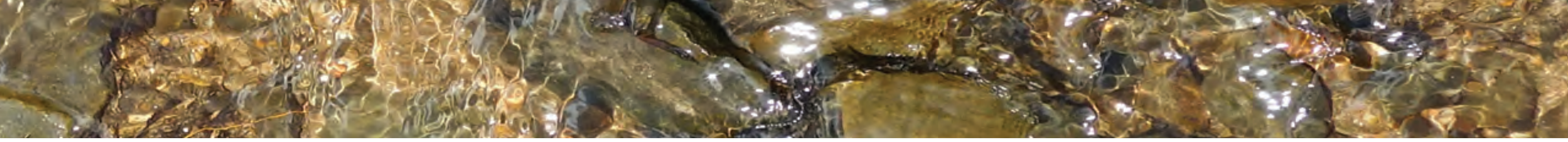


ARRESTING SLOPE WETLAND DEGRADATION

In the initial phases of slope wetland restoration in the Valle Vidal, many treatments were applied as stopgap measures (treatments that arrest headcut migration upvalley, such as a *log step fall*) to stabilize slope wetlands and halt the progress of erosion and degradation. Such measures are important components of an integrated strategy, but may not restore essential functions on their own. Specific techniques to spread water and reconnect former slope wetland areas to sheetflows and subsurface flows are critical to successful restoration and have evolved in the years following the initial stabilization measures in the Comanche Creek Watershed.

Structures that increase the length of surface and groundwater flow paths will increase the residence time of the water in the system. Such structures are common to both traditional Keyline Design and current wetland restoration treatments. They embody the overall concept of slowing, spreading, and sinking water across the landscape.

The Comanche Creek Working Group and its individual members developed nearly two decades of experience with slope wetland restoration and water spreading techniques. Evaluation of this body of work has led to many lessons learned that continue to lend themselves to both adaptive management and a desire to improve upon existing restoration tools by engaging in innovative thinking. Chapter 3 explores adaptation of the Keyline Scale of Permanence planning methodology to slope wetland restoration throughout the Valle Vidal within this context of lessons learned.



CHAPTER 3 - READING THE LANDSCAPE

MODIFYING YEOMANS' KEYLINE SCALE OF PERMANENCE FOR SLOPE WETLAND RESTORATION

The Keyline Scale of Permanence for slope wetland restoration adopts some elements from Yeomans' original list. It also ignores some concepts and adds other elements that better reflect slope wetland restoration goals for the Comanche Creek Watershed. This revised hierarchy can be applied as a guiding framework for landscape assessment, restoration treatment planning and design, and project implementation (Fig. 3.1).

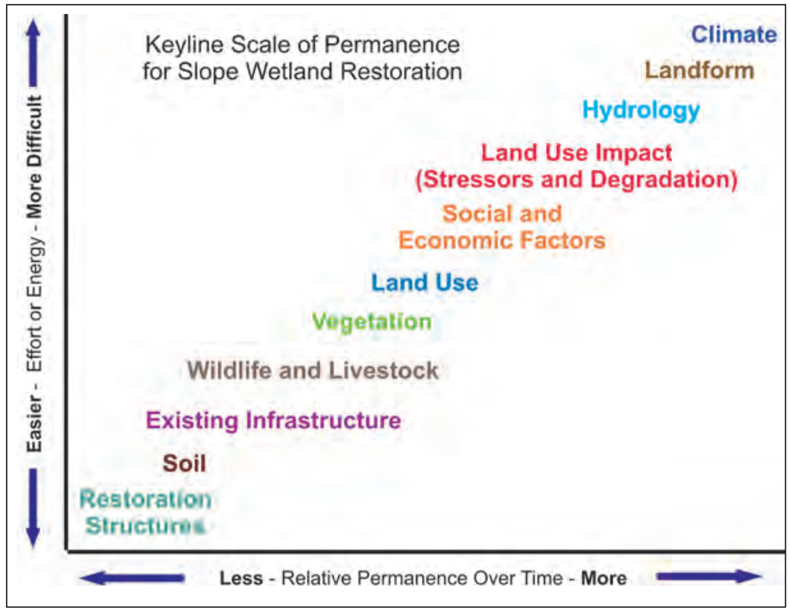


Figure 3.1. Keyline Scale of Permanence for Slope Wetland Restoration

The Keyline Scale of Permanence directs reading the landscape from the less permanent to the more permanent, highlighting the landscape pattern that is critical for water distribution and rewetting desiccated wetlands. The explicit and simple character of the Keyline Scale of Permanence method lends itself well to participatory landscape assessments with stakeholders and collaborative assessments with multidisciplinary teams.

Climate

Climate is an ecosystem driver. Though it cannot be controlled at the landscape location where work occurs, understanding how climatic forces act upon the system is an important design consideration. Climatic data are increasingly available from many locations on the internet (e.g., NOAA.gov). Important climate and weather data include types of precipitation and their seasonal variability, periodic drought cycles, and length of growing season.

Landform

Site geology and topography influence how water infiltrates soil, percolates through underlying strata, and re-emerges at the surface as springs or a gaining reach of a stream. Slope wetlands are formed in alluvial valleys, which are formed by the sediment transport and deposition actions of moving water and, in some cases, by the accumulation of highly organic soils. The topographical complexity of a wetland valley indicates where water flows, spreads, and/or infiltrates and is stored in soil. Flows may also be constricted, which results in areas that remain dry even in a valley bottom.

There may be numerous locations in a long slope in mountainous terrain that would be considered slope breaks or, in keyline terminology, keypoints (Fig. 3.2). Each keypoint could have its own effect on landform steepness and therefore on the velocity of surface water runoff, the accumulation of soil particles, soil depths, and

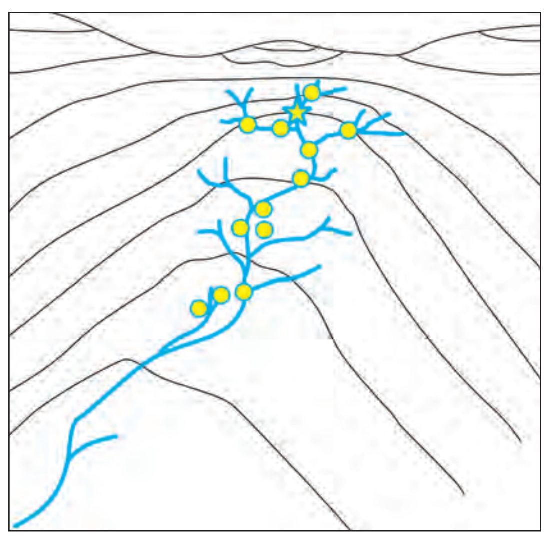


Figure 3.2. Schematic drawing of valley with multiple keypoints (yellow circles) and theoretical keypoint of valley (yellow star).

vegetation community composition. The complexity of natural landforms lends itself to the occurrence of multiple keypoints in a landscape.

Analogous to the occurrence of multiple keypoints, there may be multiple opportunities for water redistribution along one channel and within a given watershed or subwatershed. Identifying channels, ridges, alluvial fans, fens, and erosion features is critical to the identification of suitable locations and selection of appropriate stream and wetland restoration treatments.

These features indicate how many opportunities may exist to slow channelized stream flows and spread them out for better infiltration. Aspect, slope, and micro-topography patterns offer indications for the residence time of moisture on a particular site. Headwater slope wetlands are a product of the combination of surface water runoff and groundwater storage. They intercept runoff and allow water to infiltrate and reside longer in the soil, even under drought conditions (Fig. 3.3).

Figure 3.3. The bright green wetland vegetation in photo above represents locations where water resides longer in the landscape. This photograph was taken during an exceptional drought year.

Hydrology

Landform topography, along with climatic precipitation patterns and geology, determines the path water takes through the terrestrial ecosystem. In the Comanche Creek Watershed, headwater slope wetlands are dependent on both snowmelt to infiltrate and saturated valley soils and summer monsoon-driven moisture events to help sustain moisture regimes during the growing season.

Water transported downvalley as runoff behaves differently, depending on what types of topographic features and vegetation are encountered on the way. Keyline Design and slope wetland restoration treatments aim to increase the storage of water in the system by working with the surface topography to intercept and redistribute channelized flows and increase infiltration to boost subsurface flows and localized soil moisture.

Successful restoration treatments help increase water storage in wetland soils, which makes moisture available to plants for longer periods of time and typically over a greater area. The higher plant productivity in both time and space provides an abundance of decomposing plant material which increases the organic matter content of the soils. This, in turn, increases soil water-holding capacity. Discharges of clean, cool baseflow to the lower watershed are enhanced, which increases the availability of surface water for fish, wildlife, livestock, and other users.

Land Use Impact (Stressors and Degradation)

An assessment of past human activities—such as mining, overgrazing, or logging—will point toward legacy stressors that are still causing degradation, even though the activities themselves are no longer present. It is also important to consider signs of catastrophic events, such as wildfire and severe droughts, in relation to terrain stability, vegetation succession patterns, and other stressors. Stressors can also be current and may include present-day land management practices and wildlife impacts.

It is necessary to read the landscape in order to identify signs of degradation, determine its probable source(s), unravel its history, and determine potential solutions. Identifying enduring impacts from human infrastructure—such as roads, stock ponds, culverts, and bridges—is important for design purposes as well, as they may offer limitations or opportunities for using the Keyline Design approach to restoration.

For example, at a micro-topographical level, each headcut in a channel may provide an opportunity to construct a keypoint for water redistribution from the incised channel to the side slopes (Fig. 3.4). In restoration of slope wetlands, water is routed from keypoints, either to provide sheetflow over the wetland surface or to direct infiltration through capillary spaces in wetland soil.

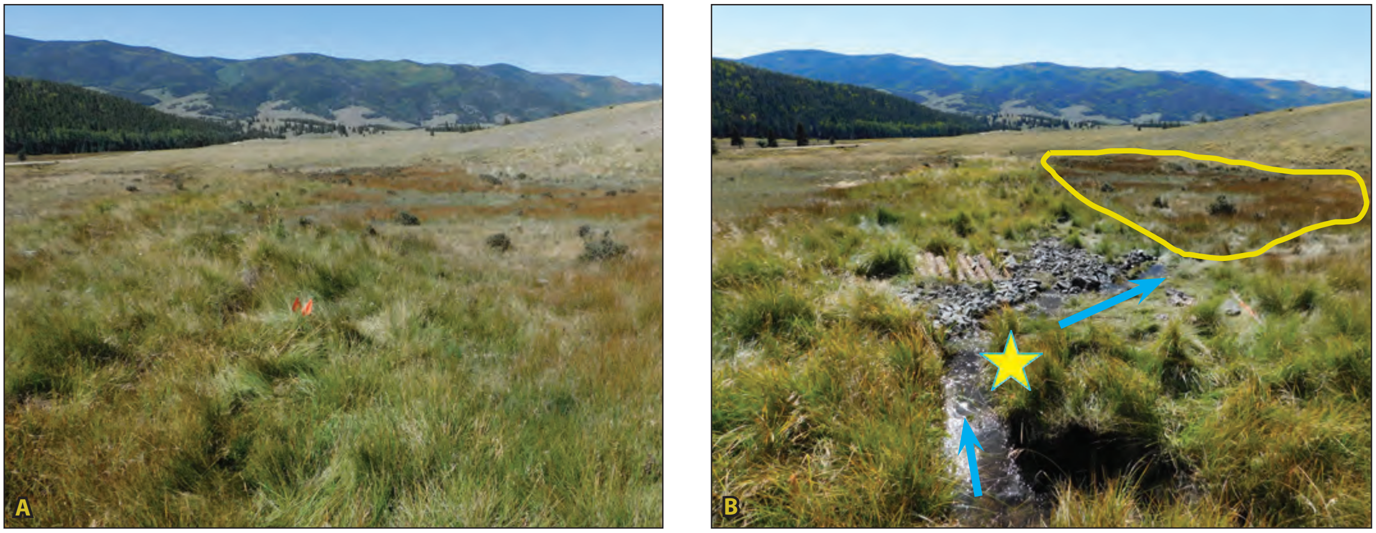


Figure 3.4A. Photograph faces downvalley in East Holman Creek before structures were built to stabilize a *headcut* (at orange flags). Figure 3.4B. The constructed keypoint (yellow star) holds and directs water across the landscape dissecting the stream's flow to a drying wetland (evidenced by *Juncus* rather than *Carex* vegetation). The yellow polygon indicates target area of *Juncus* for re-wetting. Blue arrows indicate flow path.

Social and Economic Factors

The feasibility of performing restoration activities or implementing a design may be limited by legal, regulatory, or site specific sets of rules. Identifying these rules is critical to accounting for real-world boundaries that must be taken into consideration prior to any landscape modification. Permitting processes, in addition to other economic considerations, will directly determine the scale of landscape design and restoration work.

Land ownership, easements, cultural and historic resources, and regulatory requirements associated with the National Environmental Policy Act (NEPA), Clean Water Act (CWA), and Endangered Species Act (ESA) all have a place in determining what landscape design and restoration work is feasible. On public lands, seasonal access and work restrictions impose limitations related to the timing of land management and restoration treatments. Viewshed impacts are also an important consideration.

Land Use

It is critical to understand the occurrence, timing, duration, intensity, and impacts of different types of land use. Some impacts relate to livestock and wildlife grazing; travel paths associated with hunting, fishing, and recreational activities; and upstream water diversion. The existence of rural roads and monitoring or research sites also affects wetland health and restoration design choices. The compatibility of any of these land uses with wetland restoration will not only inform project design, but also implementation choices and the probability of a particular restoration treatment's success or failure. Identifying view lines from roads and other publicly accessible vantage points onto the restoration sites will support design aspects that value scenic vistas.

Multiple purpose land use is common for most landscapes, public or private. Land use can impact any landscape-level treatment's probability of success. At the same time, the more resilient a landscape is, the more capable it is of sustaining multiple uses and users (Fig. 3.5).

©M Walton, 2018

Figure 3.5. Multiple land use (wildlife and livestock) occurs in most headwater systems, where it has the potential to make significant beneficial or detrimental contributions to overall watershed health. The photo above shows elk and cattle grazing wetland vegetation.

Vegetation

Vegetation is one of the best indicators of land health, land use (past and present), soil type, and the distribution of water in the ecosystem (both above and below ground). Vegetation records animal use of resources over time. For example, the presence of woody vegetation in a wetland that is persistent but very short indicates that animal browsing (eating the tender shoots and leaves) is an ongoing activity. Vegetation structure and species composition tell the story of stressors and degradation and are often the best indicator of restoration success.

The potential extent of wetland vegetation can be determined based on the composition and distribution of the existing plant species and the location of the historical wetland greenline as well as the current wetland greenline. This information will guide restoration professionals in determining where restoration structures may be most effective (Fig. 3.6). Vegetation communities will provide clues for determining needed destination areas for water redistribution. These may include dried out wetlands, abandoned terraces and floodplains, and areas disconnected from sheetflow and/or groundwater sources (Fig. 3.7).

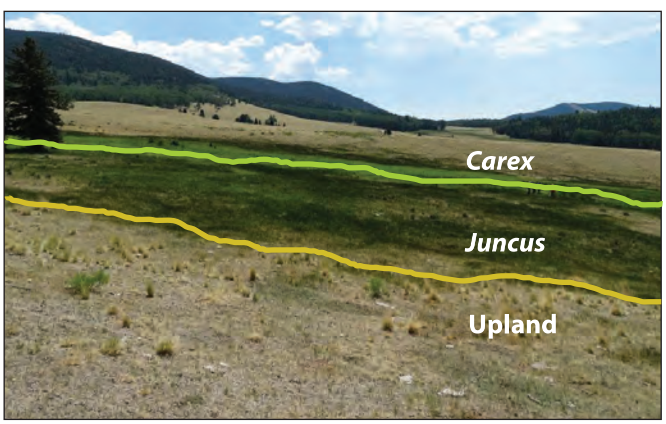
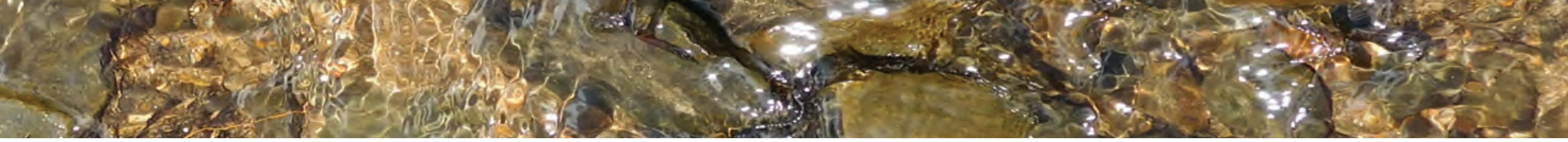


Figure 3.6. The very narrow *Carex* greenline, above bright green line; compared to the wider *Juncus* greenline, between the green and yellow lines; indicates that there is potential to re-saturate the area by redistributing water flows from incised channels higher in the valley and spreading them more widely across the area now occupied by *Juncus*.

©M Walton, 2018

Figure 3.7. This photo shows a small patch of *Carex* wetland vegetation (right), an area of desiccated upland vegetation (left foreground) and *Juncus* (darker reddish brown vegetation surrounding upland grasses), indicating that water has been captured to valley right, drying out former wetland expanses.



In areas with suitable soils, good water infiltration leads to more productive plant communities. Changes in soil moisture conditions at a wetland site will become evident by changes in the plant community composition. When a wetland becomes disconnected or dehydrated, wetland plants will be replaced by upland species, which are more tolerant of dryer soil conditions.

Wildlife and Livestock

It is important to assess the occurrence, timing, intensity, and impacts of certain wildlife and livestock populations in the area and to evaluate their compatibility with wetland restoration. Habitat improvements often draw more wildlife to an area, particularly when the availability of surface water is increased and vegetation becomes more productive. It is useful to note signs of animal trailing, as well as the occurrence and impact of ground-dwelling mammals. Browsing, herbivory, and the impacts on soil of hoof shear or burrowing activity can affect the success of a restoration project (Fig.3.8). All of these activities can impact the flow of water over the land surface.

Figure 3.8A. At the base of the field book is a Bebb willow that has been browsed (yellow arrow). If allowed to grow in the absence of heavy grazing pressure, a Bebb willow will turn into a small tree. Figure 3.8B. The photograph shows how gophers have rerouted water from a worm ditch by filling the dug channel with soil in multiple places (orange arrows).

Existing Infrastructure

Some infrastructure that affects surface water flow is obvious, such as a culvert or a road through a wetland (Fig. 3.9). Other features may be harder to observe, such as sediment-filled stock ponds.

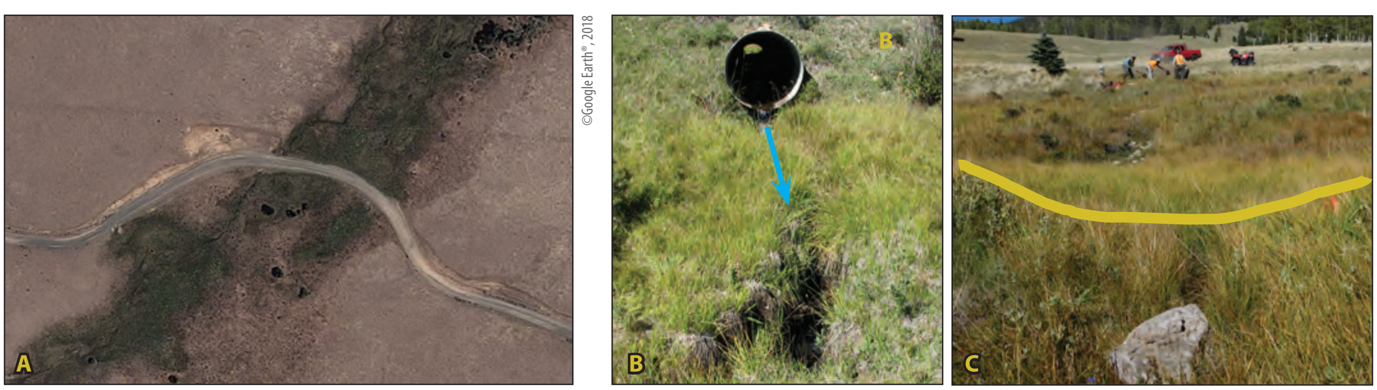
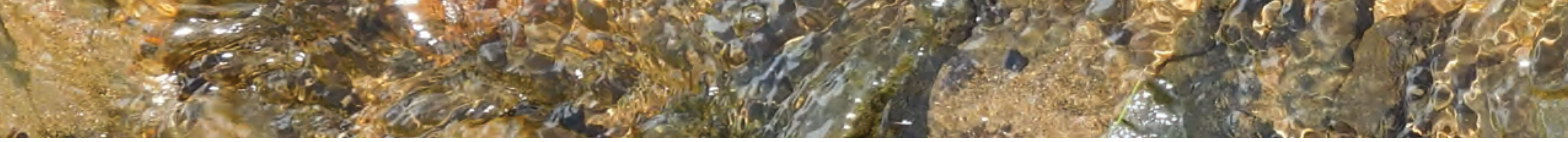


Figure 3.9A. Areal image of East Holman Creek bisected by Forest Service Road 1950. Figure 3.9B. A culvert concentrates flow, causing the channel to downcut below the culvert. Blue arrow indicates flow path. Figure 3.9C. An old stock pond interrupts sheetflow through the hillslope. Yellow line indicates approximate top of pond berm.



Features in the landscape that diminish sediment supply and interrupt sheetflow are barriers to reconnecting slope wetlands with their former water and sediment sources. However, when reading the landscape with Keyline Design concepts, these features may be thought of in a different light. New keypoints may be created when restoring old stock ponds, repairing headcuts, and installing grade controls and flow splitters. All these of these keypoints provide opportunities for converting channelized flow to dispersed flow over a greater area in order to re-saturate former wetland acreage.

Soil

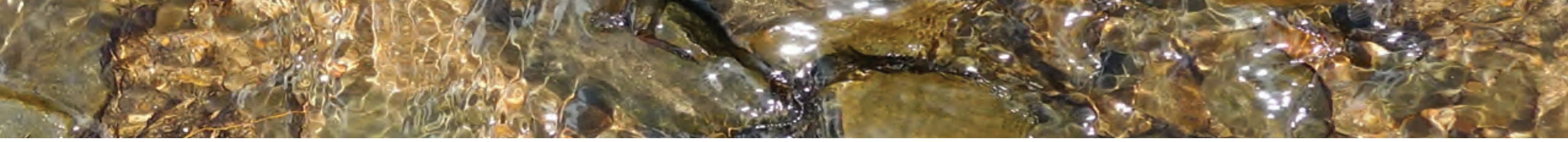
Soil type varies due to geologic parent material, erosion and deposition processes, and presence of former or current wetland vegetation. Soil texture and structure are important characteristics that impact soil stability, soil permeability, and wetland restoration potential. Based on their increased organic content and potential for holding water, only formerly hydric soils should be considered for wetland restoration. Erodibility of uplands, banks and road sides, and areas that could serve as sediment sources are important to note in relation to restoration design and treatment location. Areas with bare soil may be used as a sediment source to fill down-gradient treatments or may require a surface cover, protection from animal impacts, and/or rewetting to promote revegetation and prevent erosion.

Restoration Structures

Locations and types of restoration structures must be appropriate to the landform and focused on redistributing water in conjunction with any headcut stabilization or channel aggrading functions. Raising the grade of incised channels may be completed with many different restoration treatments (Zeedyk and Clothier, 2014; *Characterization and Restoration of Slope Wetlands in New Mexico: A Guide for Understanding Slope Wetlands, Causes of Degradation and Treatment Options,* 2014). It is important to systematically design treatments that balance the goals of spreading water as high up and as frequently as practical with the overall recovery of the slope wetland complex.

Treatments in sequence or treatment trains may be used to collect and re-spread water over a larger area. For example, in Figure 3.10A, a log flow splitter diverts water into a swale and berm system, which then further pushes water toward valley left, where a patch of Juncus shows a drying slope wetland edge. A stable return (Fig. 3.10B) is a rock, log, or sod structure that slows runoff at the point where water is dispersed over the wetland surface or returns to the channel in order to prevent erosion.

Figure 3.10A. This example of a *treatment train* begins with a log mat flow splitter connected to a rock armored lead-out berm moving water into a swale with a log and sod reinforced berm. Figure 3.10B. The treatment train culminates in a stable return composed of two rock media lunas that spread water across the target area. Blue arrows indicate flow directions.



During the assessment phase of a project, the selection of priority areas can be based on a variety of criteria such as potential for improving ecological function, ease of operation for restoration activities, restoration of the most acreage, and/or addressing the highest level of degradation. Consideration of the economic, ecological, and social costs and benefits of treatment alternatives is essential, including the do-nothing option—leaving a site in a degraded condition.

One of the most important concepts to consider is that often the feel-good work, such as treating the ugliest and most eroded component of a system (highest level of degradation), may not have the greatest effect on the function of the wetland (Fig. 3.11). Also, a headcut or gully draining a downslope wetland may require stabilization before restoration upstream will effectively increase wetland function.

Construction material sources, impacts of travel by personnel and equipment to the restoration site, and proper timing of work are all critical logistical considerations when planning restoration work in headwater systems. The final cost of a restoration effort, as well as its success, depends on careful logistical planning.

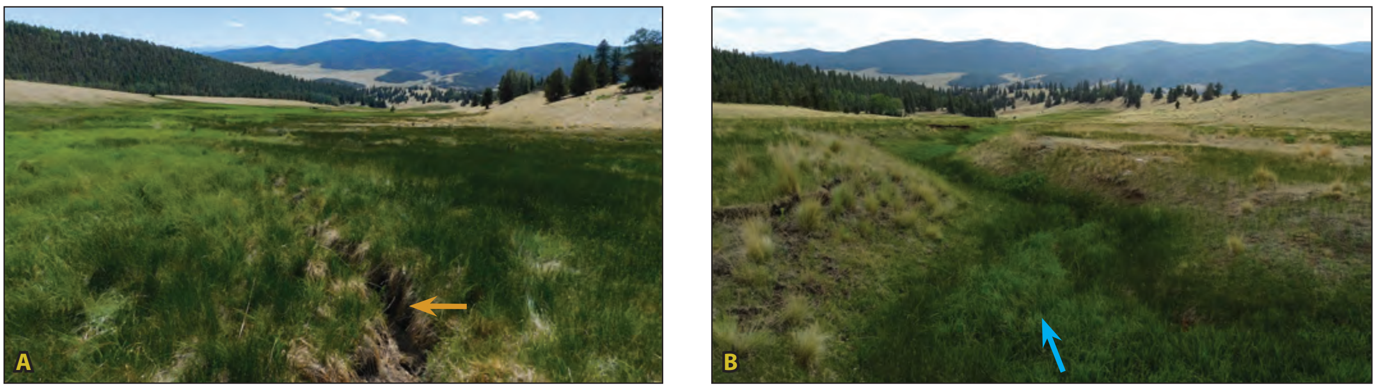
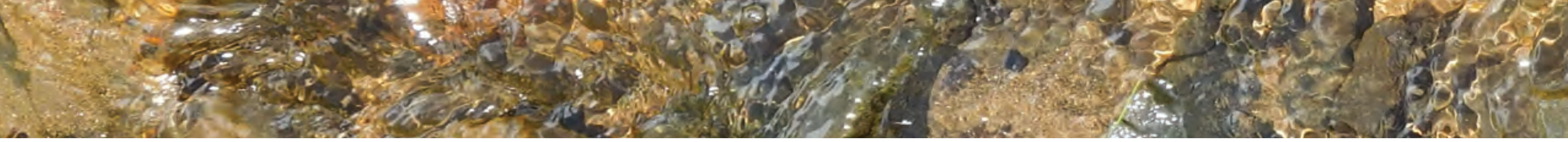


Figure 3.11A. This photograph shows an example of an easy repair using simple wetland restoration techniques. The wetland is still functioning. Addressing the channel incision (at orange arrow) will preserve function. Figure 3.11B shows a system that is severely degraded and has become an inset floodplain. Working in this system to bring the entire channel to reconnect with its historic floodplain will be expensive, but also extremely beneficial, if it is possible to restore sufficient saturation to the abandoned wetlands. Blue arrow indicates flow direction.

IDENTIFYING KEYPOINTS FOR SLOPE WETLAND RESTORATION PLANNING AND DESIGN

In Keyline Design, the keypoint is the single most important feature to be determined for landscape modification. For the purposes of headwater slope wetland restoration, there may be multiple keypoints in the landscape. The possible keypoints for the purpose of wetland restoration could include:

- Traditional keypoints as defined in Yeomans' 2002 book on Keyline Design (locations which maximize the travel time and pathways of water)
- Keypoints in high priority drainages with permanent stream flow and/or other significant water sources (springs, ponds, fens, etc.), which will likely be most important for wetlands restoration
- Areas where a structure could maximize infiltration and groundwater storage potential
- Areas where vegetation indicates that modifying hydrology and infiltration or protecting vegetation with fence exclosures will expand current wetland extent
- Sites of degradation, such as incised channels, headcuts, and animal trails that have captured water
- Existing infrastructure, such as old stock ponds, culverts, and berms, which can be used as keypoints for holding or redistributing water



Taking all possible keypoints into consideration will inform a plan that prioritizes treatment sites and defines desired ecological outcomes. Selected keypoints for the design of treatment trains should work strategically in sequence to continuously spread and respread water. Budget constraints, site conditions, access, and restoration material supply options will inform selection and prioritization of treatment sites within the entire restoration site. Restoration designers must identify the locations of channel degradation and weigh the relative costs and benefits of selecting particular keypoints for designing treatments (Fig. 3.12). Often such choices must take into account multiple logistical constraints. Smaller valleys may be of lesser significance, have a smaller wetland area, and have either intermittent or ephemeral flows and fewer water sources (smaller watershed area).

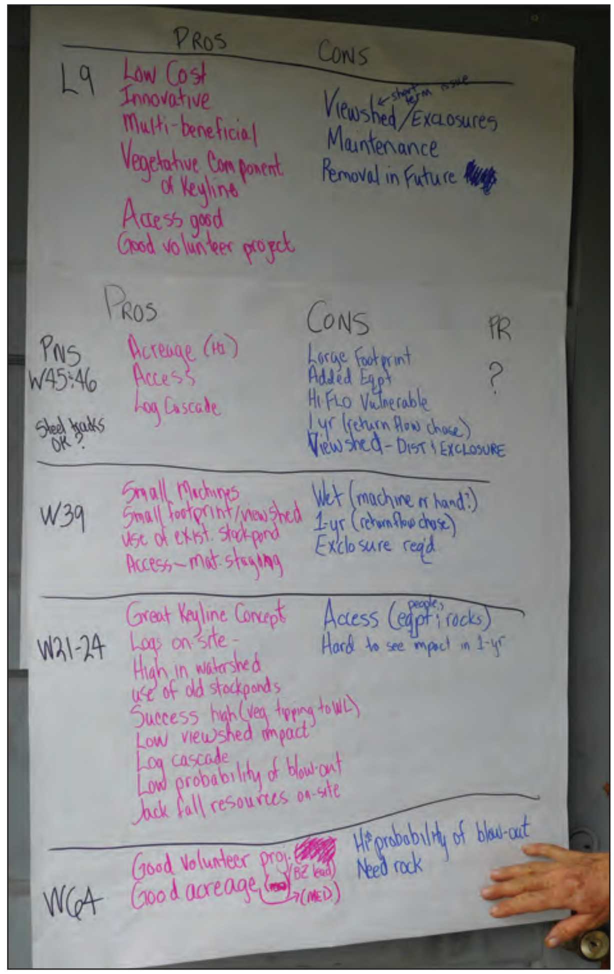


Figure 3.12. The photograph captures prioritization notes following field reconnaissance that shows project specific considerations.

Planning and design of wetland restoration projects based on Keyline Design principles and techniques is an iterative process. There is often a need for many more structures in a headwater system than most projects can fund. Once structures have been located in the field and preliminary designs for restoration treatments have been undertaken, treatments must be prioritized. It is important to consider goals in relation to project sustainability in the long-term land management in the area, along with the limitations posed on restoration options by land use and land condition.

Headcuts should be selected for treatment based on the potential to restore degraded or dehydrated wetlands. Headcut stabilization structures can be used as constructed keypoints for spreading water to restore adjacent wetlands. The most appropriate techniques for each priority headcut keypoint are selected based on area of wetland impacted, present damage, potential for improvement, and the opportunity to spread water. Logistical considerations regarding material availability and labor requirements also play a critical role in selection of the most appropriate techniques.

The opportunity to spread water is informed by valley width and slope, presence of dried wetland areas with suitable elevations relative to a channelized water source, and ability to provide a stable return to the channel. In Figure 3.13, a combination of techniques placed in sequence serves the goals of headcut stabilization, channel aggradation, and water spreading - a treatment train.

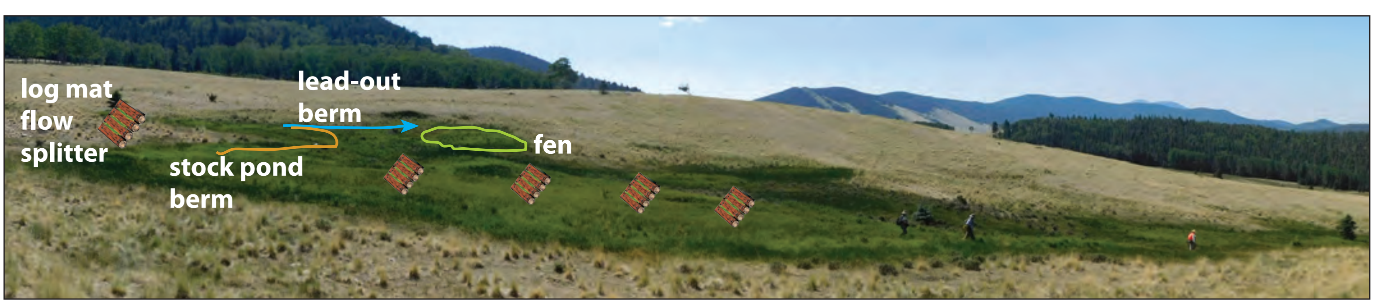
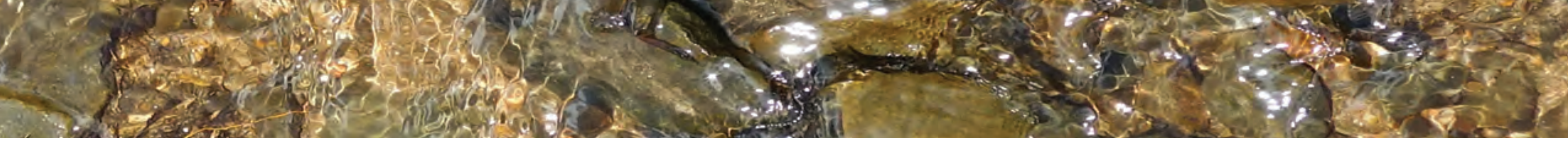


Figure 3.13. A schematic overlay on a treatment train photo in Middle Holman Creek. Water is continually spread from the main channel to wetland surfaces. Blue arrow indicates flow direction. Green polygon is a fen. Log icons indicate locations of restoration structures.



Water spreading should be designed with water infiltration in mind. Stable returns are essential features in a treatment train to ensure that the redirection of water does not result in a newly created erosion feature. Treatment train structures and their stable return(s) should be robust enough to withstand high flows and still function.

In many cases, water spreading can only be accomplished by building specific structures to redistribute water from channelized flows to the desired, farthest practical locations, using gravity and local topography (Fig. 3.14).

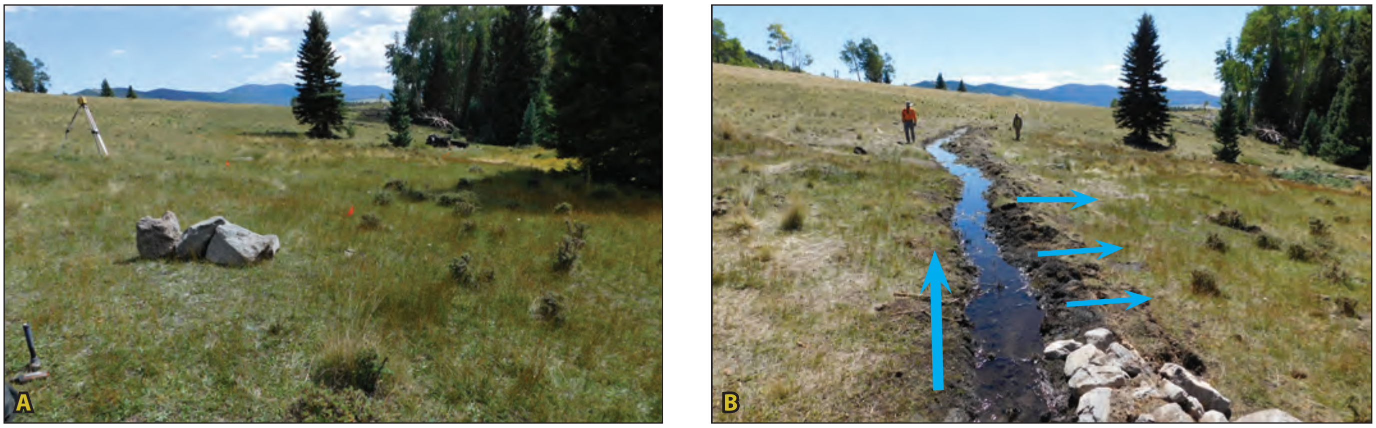
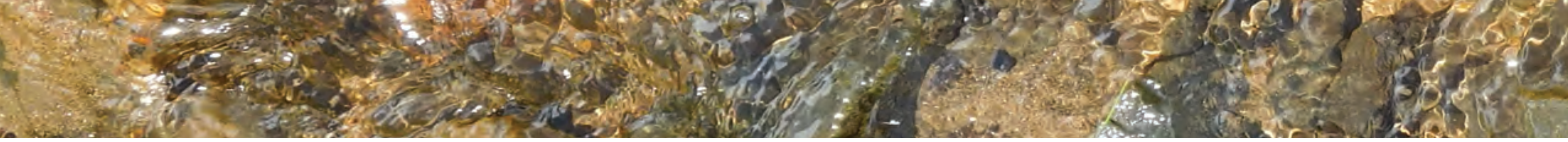


Figure 3.14A. The presence of *Juncus* (brownish-green colored rush) in the otherwise upland vegetation indicated that it might be possible to return this area to wetland obligate vegetation with increased water infiltration to the soil. Figure 3.14B. The photograph shows a constructed swale and berm at the end of a lead-out berm which moves water to the farthest extent possible. The treatment will increase water infiltration downvalley. Blue arrows indicate flow paths.

Existing infrastructure, such as old stock ponds, roads, culverts, ditches, and grade control structures can be considered as potential keypoints and expanded, extended, or modified to redistribute water. Innovative water spreading ideas inspired by the Keyline Design approach include expanding the use of a cascading sequence of structures in a treatment train. This innovative adaptation of current techniques helps spread water farther to the limits of the former wetland than would be allowed by the natural topography in its present form. Applying the Keyline Design approach to natural wetlands leads to the design of a dendritic, cascading, and ever-spreading system of structures that allows for greatly expanded water absorption and retention capacity, resulting in revived and sustained wetland areas.

The essence of the Keyline approach as it applies to wetland restoration is valley-wide, integrated planning and design of landscape features to maximize the effective use of water and other natural resources using the following steps to restore wetlands toward their maximum extent across a watershed area.

1. *Identify stressors* in order to determine cause(s) of degradation and determine if current stressors can be removed.
2. *Locate and evaluate degradation indicators* (headcuts, channelization, dry vegetation patches, etc.) as the footprint of degradation on the land.
3. *Identify keypoint water sources* (headwater streams, springs, old stock ponds, and culverts) where channelized flow can be converted to sheetflow, or water can be spread to dried wetland sites to re-saturate soils and increase vegetation productivity.
4. *Determine the topographic hierarchy and where the use of gravity, constructed land features, and stabilization structures* will hold, infiltrate and spread water (e.g., constructed keypoints).
5. *Make a concerted effort to spread water as far from the keypoints as possible.* Treatment trains move water across historic wetland surfaces at multiple keypoints.
6. *Determine priority sites* based on limitations and management objectives.
7. *Follow-up with monitoring* to ensure the treatments are working as planned.



CHAPTER 4 - TECHNIQUES FOR REWETTING SLOPES AND VALLEYS

RESTORATION TECHNIQUES IN RELATION TO DESIRED FUNCTIONS

The techniques used in the Keyline approach to slope wetlands restoration are part of a continuum of innovation, improvement, and expansion of the stabilization and rehabilitation toolbox. In addition to specific treatment techniques, Keyline Design provides several conceptual frameworks and planning tools to assist restoration practitioners, project managers, land owners, students, and regulatory agencies in assessing and designing watershed-scale restoration projects.

Slope wetland restoration treatments place emphasis on wetland stabilization and returning channelized flows to sheetflow in order to expand wetland acreage. The toolbox presented here builds on the treatments featured in the technical guide, *Characterization and Restoration of Slope Wetlands in New Mexico: A Guide for Understanding Slope Wetlands, Causes of Degradation and Treatment Options* (2014).

For clarity of presentation, the specific treatments highlighted in this chapter are divided into four main categories based on their primary function:

1. Water Spreading and Flow Splitting
2. Stabilizing and Modifying Channels
3. Integrating Existing Infrastructure
4. Managing Ungulates

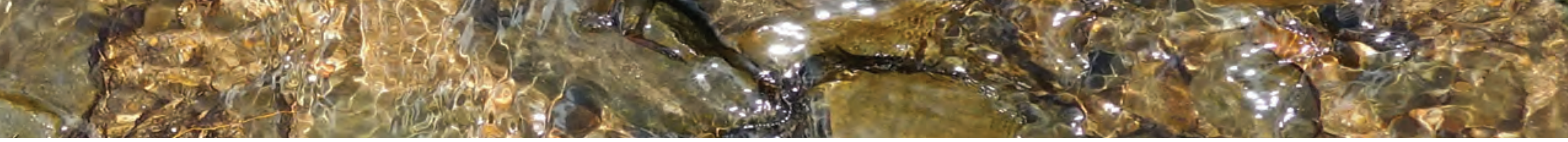
It is essential to understand that a single treatment may often be designed and located to achieve multiple functions and that treatments are best implemented in series (e.g., treatment trains) to achieve optimization of desired functions throughout a slope wetland area. Multiple structures should work in tandem to halt or reverse degradation and restore ecological function over a larger area and with better success than structures working independently of one another.

WATER SPREADING AND FLOW SPLITTING

Water spreading and flow splitting are a primary goal of many slope wetland restoration treatments. *Water spreading* refers to intercepting channelized flow and spreading it over a wider area as sheetflow. *Flow splitting* refers to intercepting a channelized flow and allowing some to remain in the current flow path while directing the rest to a different suitable area. Both strategies are designed to increase the wetted area and can be effectively implemented as a series of cascading treatments to split and spread flows multiple times prior to any return to a channel. It is important to use flow splitters that leave some portion of flow in the existing channel when downstream wetland conditions exist.

Many of the channel stabilization and aggradation techniques can be modified to include additional flow splitting functions through the careful setting of elevations. Structures such as one rock dams, log step falls, log mats, Zuni bowls, and rundowns all have the potential to be installed as flow splitters, in addition to the stabilization and/or aggradation functions for which they were originally designed (Fig. 4.1).

Figure 4.1. A log step fall to stabilize a headcut is elevated to split channel flow to a lead-out berm. The lead-out berm was excavated a few inches deep to achieve a suitable elevation for capturing and directing the flow that was split from the main channel. Blue arrows indicate flow paths.



Key considerations are the relative elevation of the upstream edge of the structure and the height of one or both banks. Each structure should be constructed according to site conditions. The upstream edge of the structure may need to be built at a higher elevation and/or a bank may need a lead-out berm or channel installed to achieve appropriate elevations for flow splitting (Fig. 4.2).

Alternatively, a water spreading or flow splitting structure can be built upstream from the headcut (Fig. 4.3). This may be a more appropriate location due to factors including the size or complexity of structure(s) needed, micro-topography and bank heights, potential area re-wetted, and/or to avoid constructing a lead-out berm. An upstream water spreading structure may be sufficient to dewater a headcut and thus avoid the need to build a stabilizing structure. A dewatered headcut is one with 100 percent of flows diverted around it in order to stop its erosive scour and migration. At sites where peak runoff might overtop flow splitter and spreader structures, headcuts can be stabilized with separate structures that do not need to serve as spreaders or splitters (e.g., Zuni bowl) (Zeedyk and Clothier, 2014).

Ensuring that structures are built and keyed together tightly enough for water to flow over them**,** rather than through cracks or gaps**,** is essential for achieving successful flow splitting and spreading functions. Road base or another coarse material can be packed between logs or rocks to achieve suitable tightness (Fig. 4.4).

Log and rock structures that are built and located properly should become colonized by existing and new vegetation over time. Where log structures are built in proximity to intact wetland vegetation, the plants should be allowed to come up through the structure as it is built. Geotextile fabric should always be used for log step falls, and the upstream components of the structures should be sealed and armored with rocks, base course, and/or sod. To promote vegetation, the geotextile fabric should not be used on the downstream end of the bottom layer


©M Walton, 2017

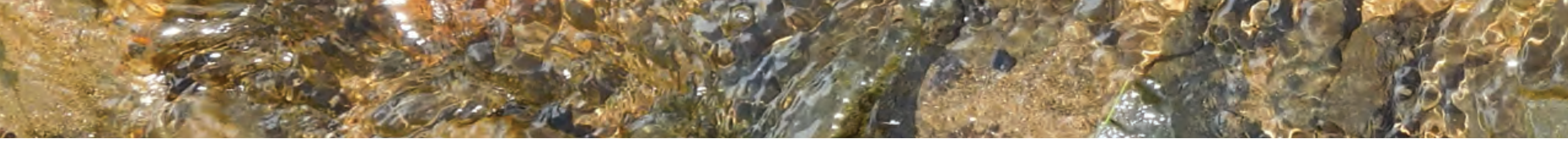
Figure 4.2. This log and rock flow splitter is built higher on the upstream side to spill water out of the incised channel and back onto the wetland surface. Blue arrows indicate flow paths.


©M Walton, 2019

Figure 4.3. This log mat flow splitter was built upstream of a large headcut. It spreads the majority of flow to valley right through a rock and log reinforced lead-out berm. Existing vegetation was carefully incorporated into the flow splitting structure and new vegetation is colonizing the treatment area. The downstream area is kept saturated but the flow splitter prevents it from receiving erosive flows. Blue arrow indicates flow direction.


©M Walton, 2017

Figure 4.4. Water flows over this log mat, which has been tightly packed with base course between logs and sealed on its upstream face with sod, cobbles, and base course (not visible). The sides of the mat are keyed into the banks at a higher elevation than its center to prevent water from going around it and causing bank erosion and possible structure failure. Blue arrow indicates flow direction.



of logs, which must be in good contact with the soil and existing vegetation. Log mats used to stabilize and aggrade channels should be built with wetland vegetation growing through them. Log mats do not require geotextile fabric beneath (Fig. 4.5).

There is a trade-off to packing the base course material so tightly that wetland vegetation cannot grow up through the structure. The decision to use base course or allow wetland vegetation to grow through the structure depends on the situation, as well as on the need for immediate stability. Generally, as a structure becomes taller or bigger, the importance of additional stability from base course increases. Base course may be used on the lower layers of log step fall structures to help prevent piping while allowing for vegetation to grow through the top layer. Staging these materials on a piece of landscape fabric allows for easier recovery of more of the material and avoids covering or damaging existing vegetation in the staging process.

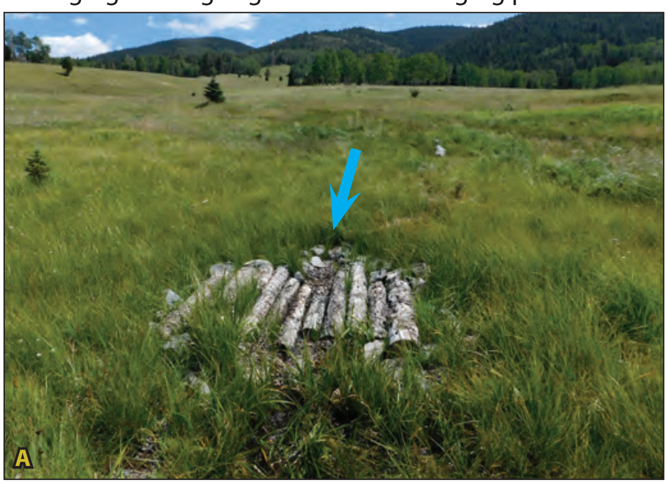
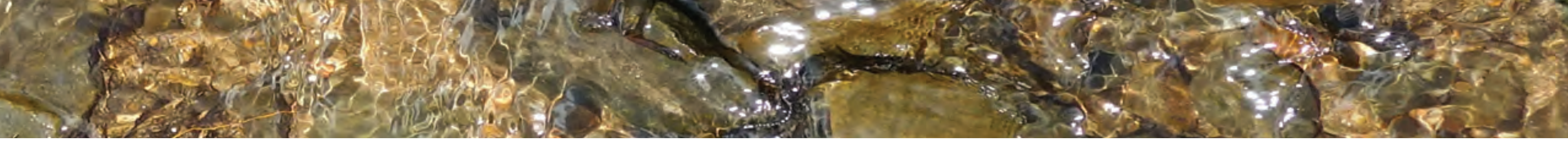


Figure 4.5A. The photo above shows *Carex* growing through a log mat. Figure 4.5B. These structures had base course materials used to key them together. Base course remains on the wetland surface. Blue arrows indicate flow directions. Figure 4.5C. shows Geotextile fabric being used to deliver finer materials to stabilize a media luna with no impact to the surrounding wetland vegetation.

When possible to implement projects over a multi-year timeline that allows for adaptive management, preventative maintenance, and the addition of more structures to optimize restoration success, it may be beneficial. However, building structures in natural ecosystems and on public lands in most cases precludes the possibility of timely maintenance and adaptive management; therefore structures and treatment trains must be built to last. This translates to design specifications that favor simplicity, adequate dimensions, and durable materials. Optimal sizing and siting of structures and treatment trains with the selection of simple, minimally invasive, fail-safe materials, are of critical importance to long-term success. Adequate armoring of structures can be an effective means to increase their robustness and longevity (Fig. 4.6).

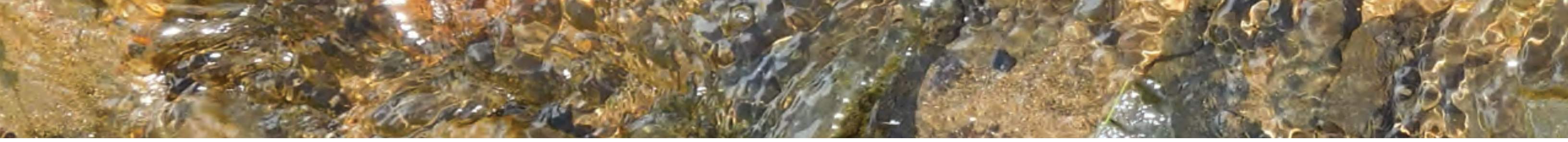
Figure 4.6. This swale was lined with angular cobble to increase stability because the wet meadow vegetation is currently not adequate to hold soil in a large flow event. Additional armoring is necessary until the swale has had some time to spread water and convert the dessicated wet meadow to wetland vegetation. Armoring also provides much needed protection from animal impacts, especially hoof sheer. Blue arrows indicate flow paths.



The relative elevation between the upstream edge of a stabilization/aggradation structure and its lead-out channel determines how much flow remains in the existing channel and how much is split out to rewet former wetland areas. This is a constructed keypoint. The dimensions of the lead-out channel, as well as the angle at which a split flow exits the main channel, impact how well a flow-splitting structure functions. The cross-sectional area of the lead-out channel should match that of the main channel, but the lead-out channel is often built wider and shallower than the main channel to slow the flow of water. Consideration of both base flow and high flows (snow melt and storm surges) should be included when determining the appropriate type of flow-splitting structure, its material(s), and its relative elevation (Figures 4.7 and 4.8).

Figure 4.7A. A log step fall in West Holman Creek, serving as a flow splitter, stabilizes a head cut and splits water flow into an armored lead-out channel to a reinforced spreader swale, while allowing some flow to remain in the current channel to support downstream wetland vegetation. The log step fall is the constructed keypoint. Figure 4.7B. After one year, the swale is allowing water to both infiltrate below the berm and spill past a stable return at the end of the berm to rewet former wetland. Figure 4.7C. In this photo, sheetflow from the upstream lead-out swale and berm (Fig. 4.7A) is visibly travelling downvalley past the large and seedling conifers visible in these pictures (white arrows). Blue arrows indicate flow paths.

Figure 4.8A. A log step fall with flow splitter directs water from the channel to rehydrate a disconnected slope wetland area towards valley left. Blue arrows indicate flow paths. Figure 4.8B. This photo shows the same structure; built higher on valley left to direct flow downslope. Black arrows indicate flow direction across structure.



Lead-out Berm

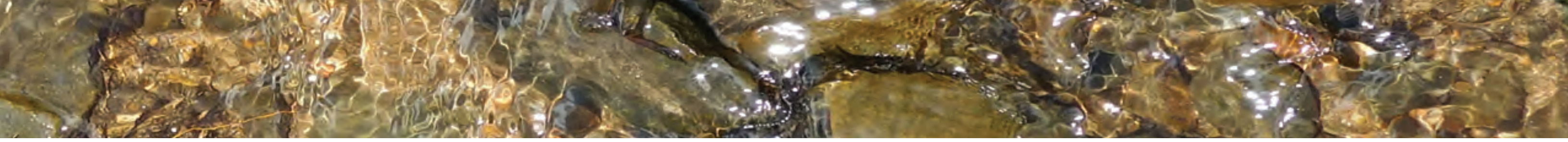
A *lead-out berm* is typically added on to another structure, such as a *log step fall* or *one rock dam*, to direct water out of an incised channel or area of concentrated flows. The elevation of a lead-out berm is set in relation to the upstream edge of the channel-stabilizing structure and extends for the distance needed to optimize the wetted area and prevent water from returning to the original channel too quickly. Lead-out berms can be created using a combination of sod, logs, and rock, and can include an excavated channel as needed to achieve the target elevations. A lead-out berm may direct flows into a reinforced spreader swale to achieve additional wetted area, or it may disperse water as sheetflow into the micro-topography of the area (Fig. 4.9).

Figure 4.9. A rock armored lead-out berm and excavated channel split flows into a log reinforced spreader swale in the West Holman Creek drainage. Blue arrows indicate flow paths.

Reinforced Spreader Swale

A reinforced spreader swale is implemented at a maximum two percent slope from its source to termination. Based on availability, spreader swales are reinforced with some combination of logs, rock, and sod (Fig. 4.10). Logs and rocks are keyed four to six inches into the ground and then backfilled with sod and earth from the swale on the upgradient side. The cross-sectional area of the spreader swale should match the cross-sectional area of the channelized flow, and generally should be wider and shallower to promote slower, lower-energy flow. Water moving slowly along the spreader swale has a chance to infiltrate into the soil and seep through the berm as it reaches saturation.

Figure 4.10A. The location for the log mat flow splitter was surveyed to ensure that water could be moved out of the channel at the proper elevation. Figure 4.10B. A swale was created to receive the water diverted from the channel by the log mat flow splitter. Figure 4.10C. The log structure diverts water to the swale. Figure 4.10D. A log mat is installed in the main channel below the flow splitter to raise the grade of the incised channel and further spread water over the wetland surface. Blue arrows indicate flow paths.



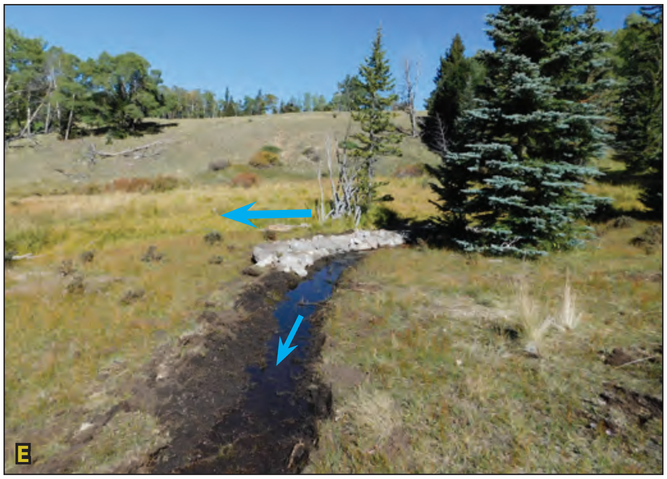
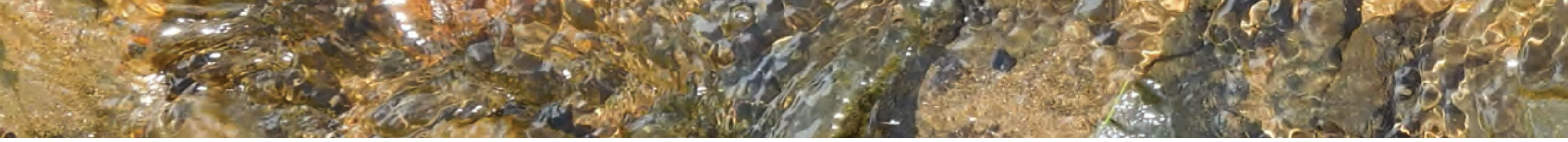


Figure 4.10E. A rock reinforced berm keeps the water in the swale. Figure 4.10F. Logs were buried in the downvalley edge of the swale to create a slightly higher berm. Blue arrows indicates flow paths.

Figure 4.10G. Elevations were surveyed so that the swale was not at too steep an angle on the hillslope, which would have caused erosion. This also created a swale that followed the natural topography and not a straight line across the slope. Blue arrows indicate flow paths. Figure 4.10H. The logs were keyed into the soil surface to minimize piping (leakage) underneath, then covered with sod.

Figure 4.10I. One day after completion of the treatment train, water reaches the far end of the swale and berm structures. Figure 4.10J. After one year, the structures are saturating the former wetland downslope.



The final outflow from a spreader swale should be installed to produce sheetflow. The site where the sheetflow re-enters the channel must be stabilized and protected with a stable return structure. Channel stabilization structures such as one rock dams or rock armoring may be added along the length of the spreader swale as needed. A reinforced spreader swale can extend water over longer distances than modifications that rely on natural topography alone. This provides opportunities to rewet suitable areas that may have become topographically isolated from current water flow path (Figures 4.11 and 4.12).

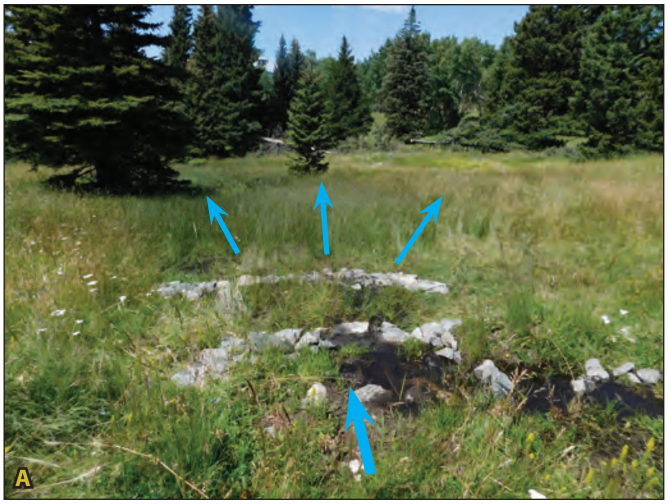


Figure 4.11A. The constructed keypoint diverts water from the channelized source via a lead-out berm to a reinforced spreader swale, sheetflow spreading structure, and stable return. Figure 4.11B. This photo shows sheetflow below a stable return.
Blue arrows indicate flow paths.

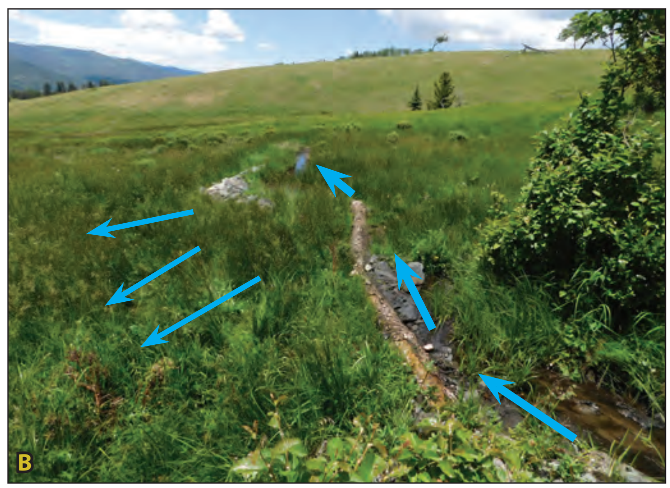


Figure 4.12A. Rock armor and excavated sod are used to create a lead-out berm to wet a reinforced spreader swale in East Holman Creek. Figure 4.12B. This photo shows water flowing to the end of the berm, then traveling downslope across another structure. Figure 4.12C shows outflow from the berm is being spread from upslope, with a *rock media luna,* to an additional target area. Blue arrows indicate general flow directions.

STABILIZING AND MODIFYING CHANNELS

Bank Cut and Channel Fill

Figure 4.13. An incised channel bisecting this slope wetland complex in East Holman Creek has lowered the localized water table and caused the bank vegetation to dry out, leaving the channel vulnerable to further degradation. The channel is being stabilized by using a mini-excavator to collapse the high banks in order to raise the grade. Blue arrow indicates flow direction.

Many slope wetlands have narrow, incised channels with undercut and/or dehydrated banks. Incised channels move water through the system faster, draining the surrounding wetland and decreasing opportunities for overbank water spreading, which results in dehydration of the wetland area. The "bank cut and channel fill" treatment is designed to raise the channel bed elevation and rehydrate streambanks and floodplains with the potential for flows to overtop banks and spread as sheetflow. This technique is suitable for channels narrow enough to be completely filled with collapsed bank materials and associated armoring. Channels less than 18 inches deep are ideal, although it may also be suitable to use this technique on larger incised channels as well. This can be described as "re-zipping" the watershed to the extent that it is practical, given current site conditions and available restoration resources. This technique works best with wetland *Carex*.

The method is to mechanically collapse banks, starting from 6 to 18 inches beyond the bank edge down into the channel on both sides. Solid contact between bank materials and the channel bottom is essential to avoid piping beneath the fill (Fig. 4.13). New banks are sloped gradually to produce a modified channel at a higher elevation, with more flood plain connectivity for water to spread out from the channel. Rock armor can be installed along the reach and/or periodic grade control structures can be added to increase stability while vegetation becomes established. Treated areas may also be covered with slash to manage animal impacts to recovering vegetation (Fig. 4.14).

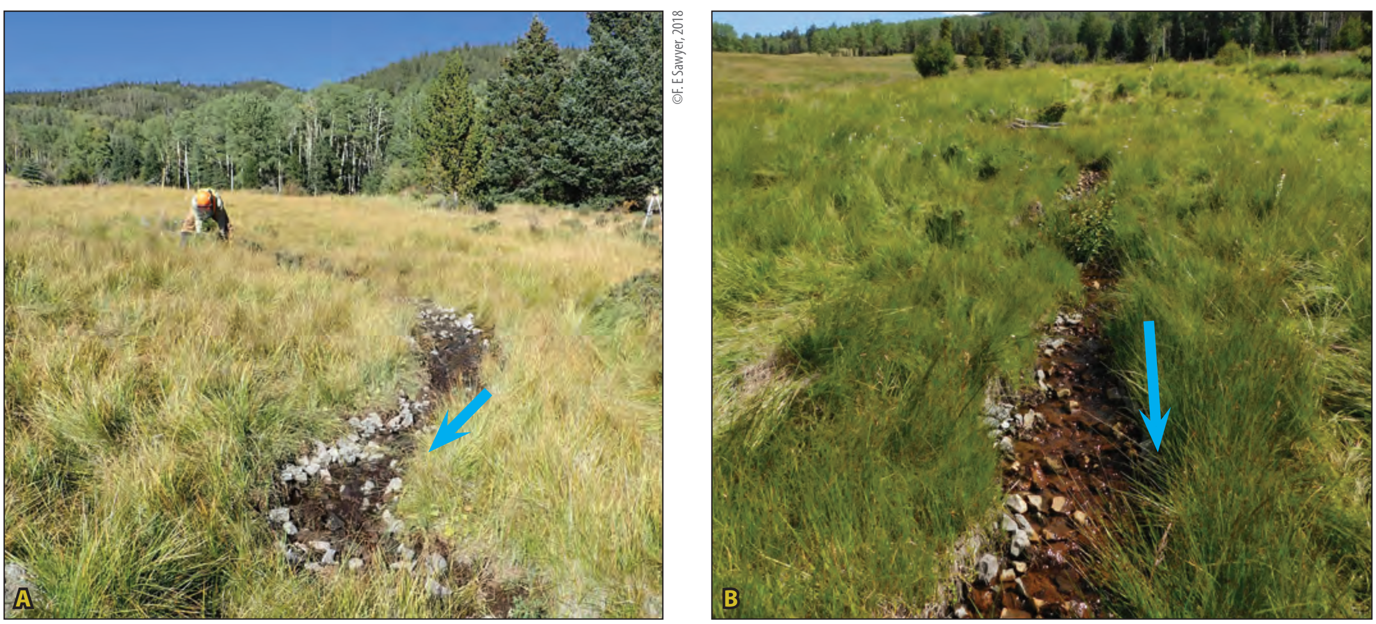
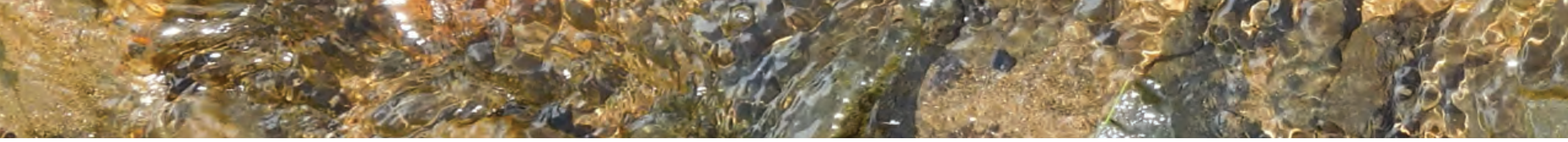


Figure 4.14A. This modified channel above was stabilized with rock armor. One rock dams were also installed as needed to further stabilize and aggrade the channel, while spreading sheet flows back onto the wetland surface. Figure 4.14B. This channel remained stable the following year. Sheetflow was re-established during snowmelt, restoring floodplain connectivity. Blue arrows indicate flow paths.



The reconfigured channel is anchored by a log mat located at a constructed keypoint (previously a headcut) and rock armored just above gradient in order to direct water to a desiccated wetland downvalley to the right (Fig. 4.15).

Figure 4.15A. In East Holman Creek, an incised channel with high and dry banks was mechanically collapsed to form a modified channel, which was armored with cobbles and integrated with down-gradient stabilization and flow-spreading structures. Figure 4.15B. In June of the following year, the structure was functioning properly to spread sheetflow to the former wetland on valley right. Blue arrows indicate flow directions.

INTEGRATING EXISTING INFRASTRUCTURE

Integrating infrastructure that is currently planned, in use, or abandoned (such as stock ponds, roads, and culverts) provides opportunities to enhance restoration objectives. Strategies for managing runoff from roads, including proper siting of new roads, is covered extensively in *Water Harvesting from Low-Standard Rural Roads* (Zeedyk, 2006).

Culvert Outflow Management

The use and function of culverts is to create concentrated flows that pass water and sediment under a road. Often the outflow of a culvert is high energy and carries a high sediment load. This concentrated discharge has the potential to create scour pools, contribute to channel incision, disrupt channel hydraulics, and create debris deposits. For more information on culvert impacts on streams and wetlands with restoration options, see Zeedyk and Clothier (2014) and *Characterization and Restoration of Slope Wetlands in New Mexico: A Guide for Understanding Slope Wetlands, Causes of Degradation and Treatment Options* (2014). Identifying culvert locations and understanding the current impacts of culvert discharges are important in developing effective strategies to mitigate adverse impacts and turn concentrated flows into resources for wetland restoration. Water-spreading techniques can be used down gradient of a culvert to achieve multiple functions through treatment trains that stabilize, aggrade, split, and spread flows.

Stock Pond Reintegration

Stock ponds have been constructed throughout the western United States, including many in slope wetlands and fens. Stock ponds are often located in existing channels, have feeder channels that bisect landscapes to capture and concentrate runoff, or are punctured into fens and other features to access groundwater resources. During field assessment and design phases, stock pond locations should be identified, analyzed for functionality, and considered within the context of project-specific restoration goals.

Stock ponds vary in terms of condition, function, and location in the landscape, which informs potential integration into larger restoration strategies. Stock ponds in the context of slope wetland restoration planning are almost always to be considered as keypoints for restoration planning. They can be incorporated to increase water retention, detain and slow down water during high flow events, spread flows via lead-out channels, and receive flows split from an incised channel. Reintegration of stock ponds uses many of the same principles as plug-and-pond and plug-and-spread treatments, as described by Zeedyk (2015) and Zeedyk and Vrooman (2017).

The breached berms of old stock ponds can be plugged to create a large swale and berm structure. If a stock pond no longer functions as a pond due to siltation, an additional swale and berm can be constructed to direct water away from the channel below the pond spillway to create a longer flow path through the system.

Plug, Split, and Spread

Stock ponds with breached berms or existing spillways can be plugged with earth, rock, and/or logs; and lead-out channels can be implemented to spread water flow over greater areas (Fig. 4.16). The relative elevations of a plug and lead-out channel will determine how flows are split between potential pathways.

Figure 4.16A. This photo shows a non-functioning stock pond with a breached berm (yellow line) in Middle Holman Creek. Figure 4.16B. This photos shows the breach plugged. A treatment train was installed at the pond spillway to send water to drying wetlands on valley right. Blue arrows indicate flow directions.

Porous Plug with High Water Spreader

Porous plugs are typically located in existing spillways or breached berms and can be built with rock large enough to withstand the high flows in a specific drainage. The porous plug should allow some water to seep through in order to maintain downstream wetland vegetation yet promote upgradient ponding in the old stock pond to increase retention and infiltration of water. At high flow, the berm should be capable of retaining enough water to allow for flow splitting directed to a constructed high-water spreader (Fig. 4.17).

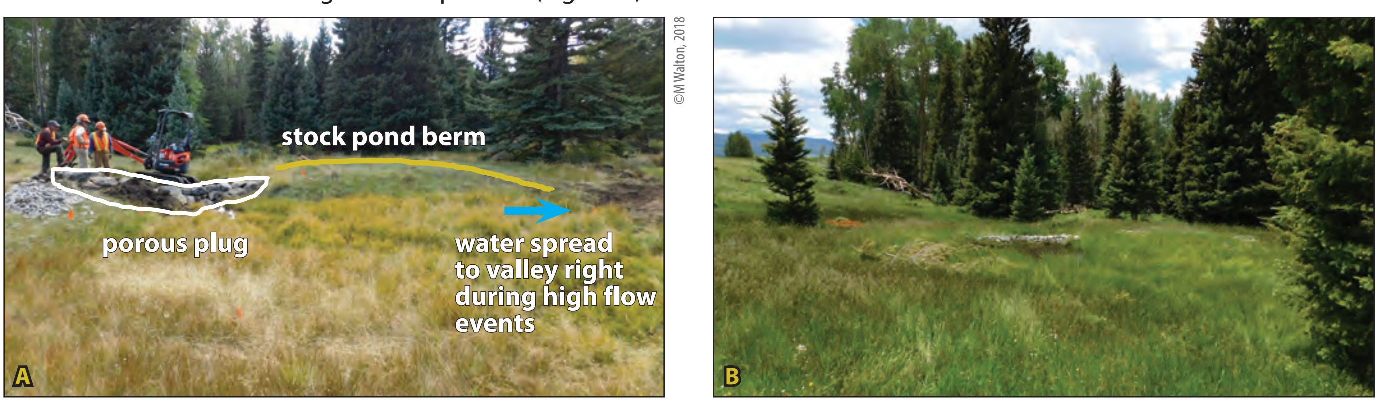
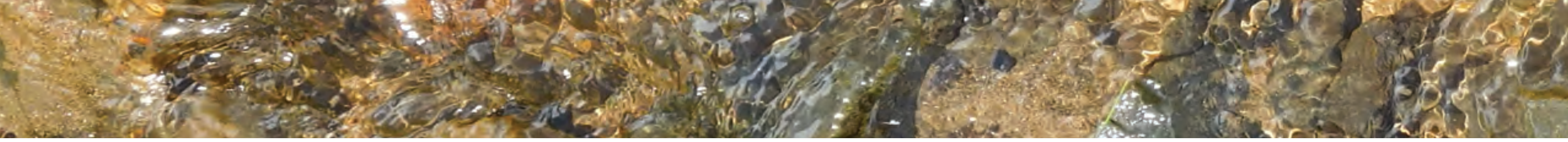


Figure 4.17A. A porous plug (white polygon) was installed in the incised creek channel at end of an old stock pond berm (yellow line). The structure increases ponding upstream of the plug while allowing some water to move slowly through the plug to support the downstream riparian channel and wetlands. A high-water lead-out channel was created to send water to valley right, where it can rewet former wetlands in the middle of the valley. Blue arrow indicates flow path. Figure 4.17B. After one year the plug has slowed water flow through the system and increased wetland vegetation density.



The high-water spreader should be lower than or equal in elevation to the top of the porous plug to direct high-water flows over a greater area. The structure visible in Figure 4.17 was checked with a laser level to ensure that the elevations were correct, but even in the high-water year of 2019, the high water flow never spilled into the adjacent wetlands. The high porosity of the plug and increased water infiltration of the soil may have been important factors limiting overflow.

Retain and Spread

A stock pond's existing capacity to retain water can be integrated to add water-holding capacity to a treatment area (Fig. 4.18). Flows that exceed the water-holding capacity of the stock pond should be directed via a lead-out berm into sheet flow in the natural micro-topography or into a reinforced spreader swale to maximize the wetted area.

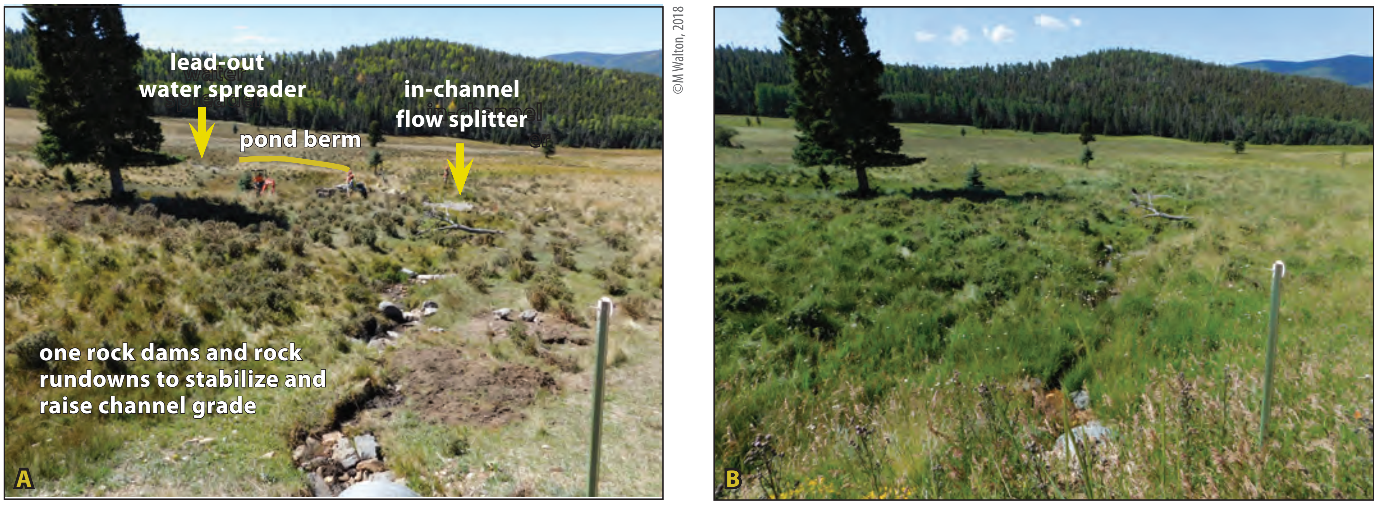


Figure 4.18A. One rock dams and rock rundowns stabilize channel and raise channel grade. An in-channel flow splitter directs a portion of the concentrated runoff from a culvert into an abandoned stock pond. The stock pond provides increased water-holding capacity. A rock-lined spreader swale disperses outflow as sheetflow across the wetland surface. Figure 4.18B. More dense wetland vegetation is apparent in 2019, which was a wetter year than 2018. Structures were augmented in 2019 to improve their performance.

Spreading Concentrated Flows

If a culvert outflow path is not stabilized, a gully will inevitably result due to increased flow velocity and flow concentration in the culvert. However, the outflow path from a culvert can be considered a keypoint, which presents an opportunity to stabilize and aggrade the incised channel below the culvert (Fig. 4.19) and integrate it into a water-spreading treatment train.

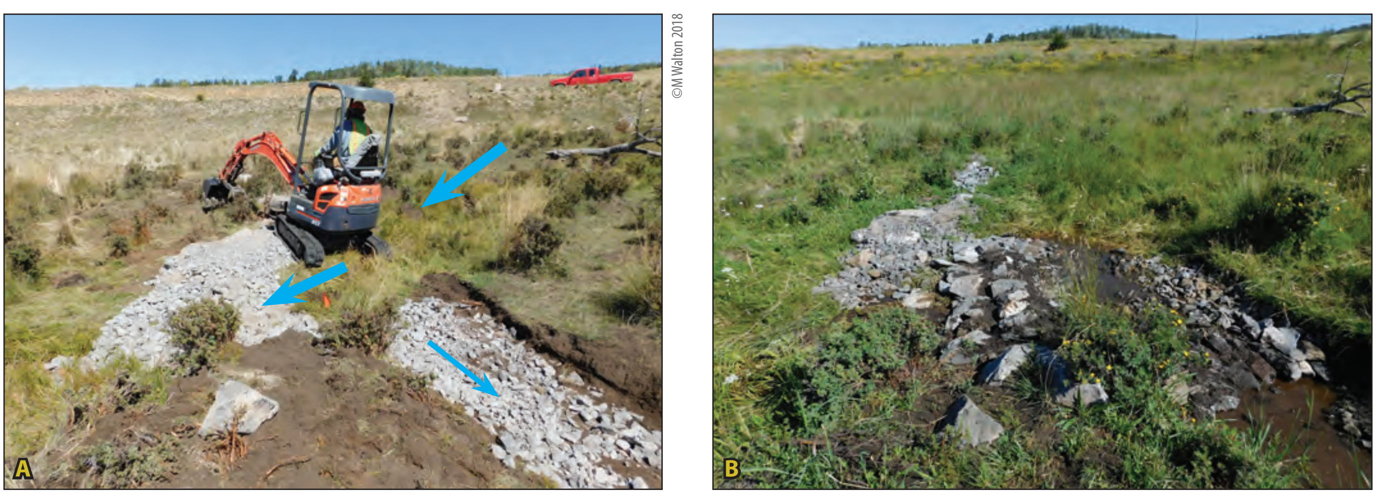
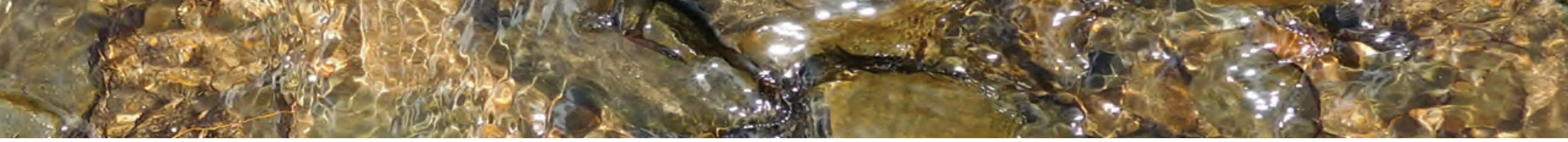


Figure 4.19A. A rock flow splitter was constructed in this incised channel to direct water concentrated by an up-gradient culvert into an abandoned stock pond. Blue arrows indicate flow paths. Figure 4.19B. Adaptive management was implemented with larger rocks to raise the elevation of the flow splitter the year after the splitter was installed, so that it could perform as intended.



Alluvial Fan Reconnection

Debris deposits and flows captured in incised channels can damage and dehydrate alluvial fans (Fig. 4.20). Removal of debris deposits and application of a spreader treatment can help reconnect concentrated flows from a culvert to an alluvial fan to help restore its natural water-spreading functions.

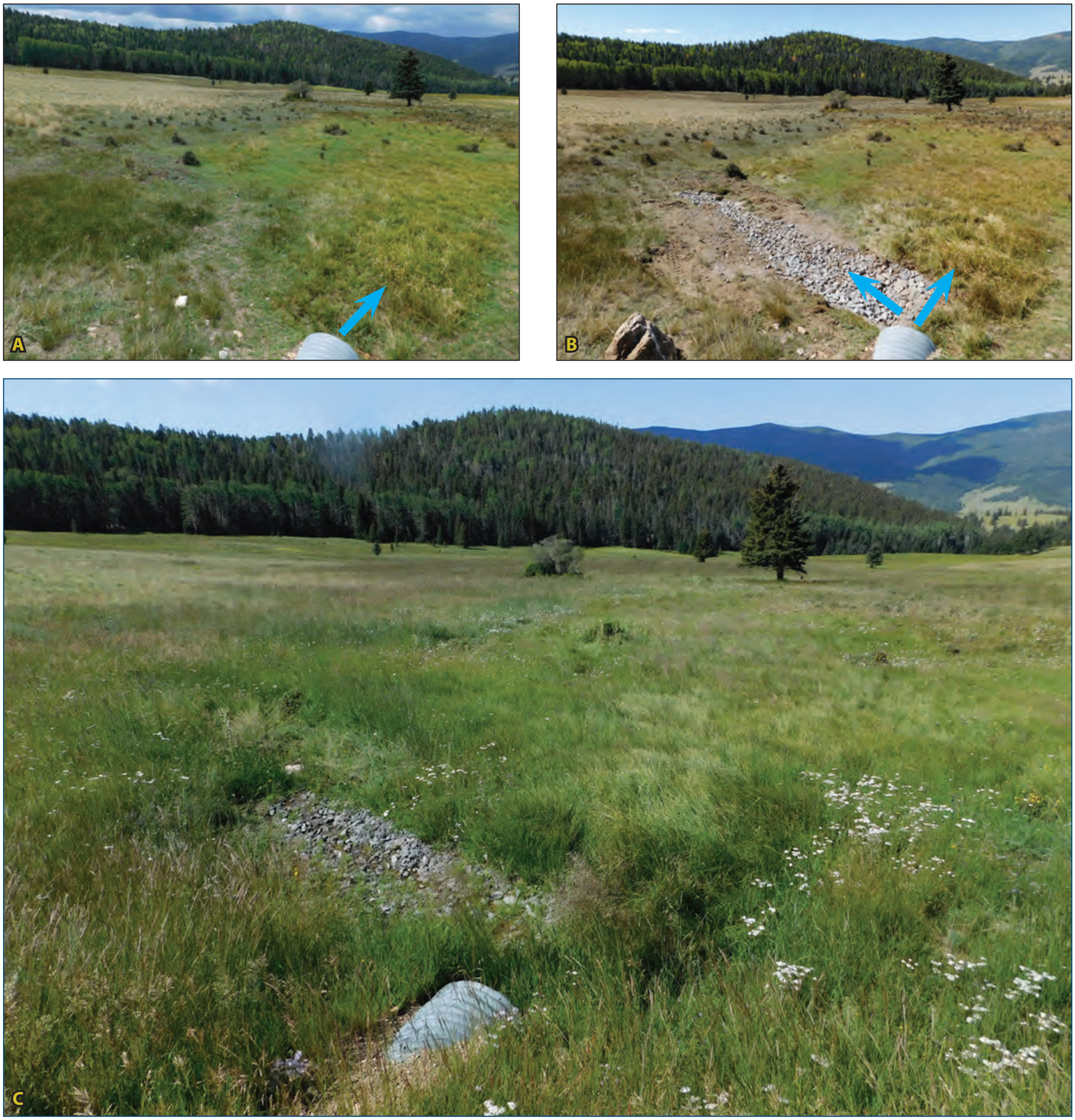


Figure 4.20A. This photo shows sediment deposition from a culvert constricted flow path over an alluvial fan. Figure 4.20B. The sediment deposit was removed and a reinforced spreader swale was installed to convert concentrated outflow from the culvert into sheetflow over a greater area. Blue arrows indicate flow paths. Figure 4.20C. After one good water year, the restored sheetflow into the wider area resulted in more productive vegetation.

MANAGING UNGULATES

Managing for animal impacts is a key consideration for restoration in headwater wetland scenarios where ungulates are common. Because ungulates can be stressors, it is critical to protect areas where water will be flowing over disturbed soils and/or where open water will exist.

Slash Mats

Methods of protecting these sensitive areas include armoring, fencing, and slash mats (Fig. 4.21). Treatments to manage animal impacts, such as slash mats and drift fences are covered in *Characterization and Restoration of Slope Wetlands in New Mexico: A Guide for Understanding Slope Wetlands, Causes of Degradation and Treatment Options (*2014).

Tree Felling

Large fir trees can be felled at the wetland edge to open the canopy and provide protection from all but the most determined ungulates while the restoration treatments take effect (Fig. 4.22).

©M Walton, 2019

Figure 4.21. Slash can be used to provide short term protection from hoof shear caused by ungulates.

©M Walton, 2019

Figure 4.22. Large fir trees felled at the edge of the wetland will help deter ungulates and open the canopy for sun-loving wetland species.

Hedgerow Exclosures

Animal exclosures can be built at keypoints to promote the establishment of woody vegetation, mimicking the hedgerows of traditional Keyline Design (Fig. 4.23). In specific locations, elongated exclosures on contour containing woody vegetation can also be used to slow and spread surface flows by acting as a vegetative berm on the hillslope. Such locations then become constructed keypoints for intercepting flows and spreading them toward the historical wetland greenline. At the same time, hedgerow exclosures can perform as living snow fences, shading structures, and windbreaks.

Some slope wetlands in the Comanche Creek Watershed have historically been habitat for woody vegetation, such as Bebb willow. Currently, this woody vegetation is kept in a browsed state and does not have an opportunity to grow to full height. Areas of high concentration of browsed woody vegetation provide an opportunity to use elongated hedgerow exclosures along the contour to encourage it to grow above browse height and provide additional ecosystem services, such as water-spreading and micro-climate creation (Fig. 4.23). Once the woody vegetation reaches an appropriate height, the exclosure fencing can be removed and reused to create another hedgerow exclosure.

Past treatments in the Comanche Creek Watershed have required maintenance and have remained vulnerable to animal impacts where adequate measures for protection and additional stabilization were not undertaken. Structures should be built with enough protective measures, along with careful implementation of constructed keypoints, to minimize the need for maintenance and manage the risks of damage from animal impacts. Using adaptive management to modify and/or expand treatments as needed and providing preventative maintenance is ideal when project budget and timeline allow.

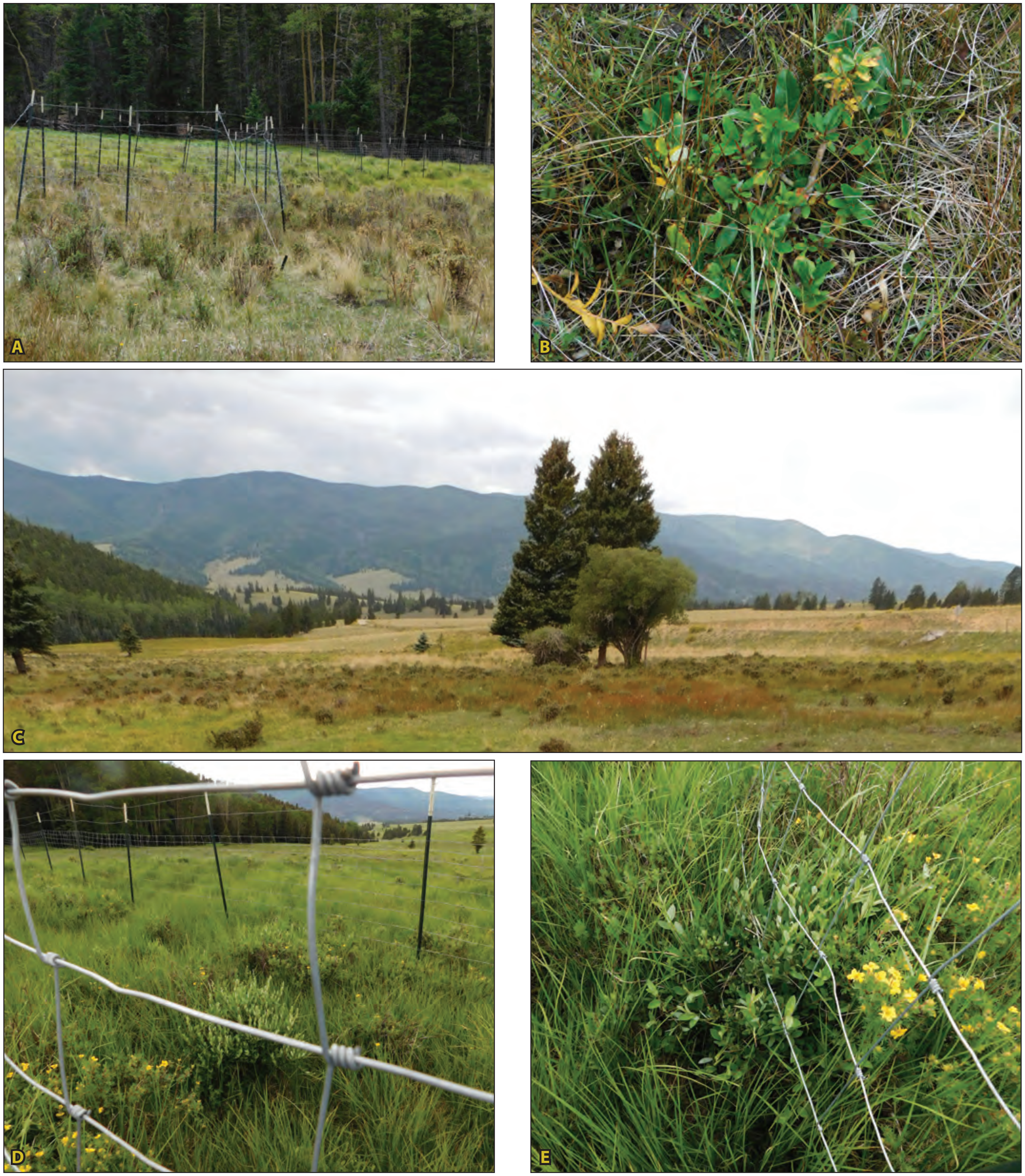
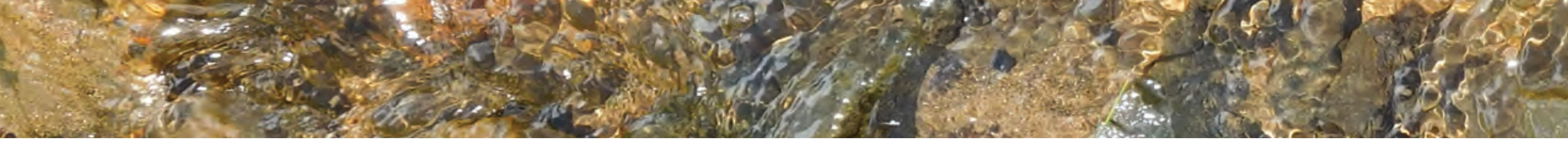


Figure 4.23A. Exclosures can be installed on contour to help spread high flows while protecting Bebb willow. The goal is for the Bebb willows to grow above browse height, form a living snow fence, and modify microclimate conditions. Figure 4.23B. Repeated browse keeps the Bebb willow close to the ground. Figure 4.23C. The broccoli-shaped tree in the middle of the photo is a Bebb willow that survived prolonged browse and grew above browse height. Figure 4.23D. This photo shows willow growth after one year (bright green leaves center). Figure 4.23E. A Bebb willow in this photograph is bisected by the exclosure fence. The left side is browsed, while the right side has been able to grow vertically because it is protected from ungulates by the fence.



CHAPTER 5 - CONCLUSIONS AND FUTURE DIRECTIONS

ASPECTS OF TRADITIONAL KEYLINE DESIGN ADAPTED FOR SLOPE WETLAND RESTORATION

The Keyline Design approach to restoring farmland and improving land productivity can be adapted to contribute to the existing restoration toolbox for headwater slope wetland restoration in natural settings. Important components of the approach are compatible with restoration goals. Keyline Design emphasizes planning a systematic assessment of water-harvesting and water-spreading opportunities, ideally starting at the top of the valley with the most potential for positive results from manipulating water flow and infiltration. The Keyline Scale of Permanence, as adapted for wetland restoration, offers guidance for wetland restoration assessment, design, and implementation, and may help practitioners recognize and refine opportunities to spread water.

Using Keyline Design principles successfully in headwater wetland ecosystems requires a valley-wide approach that emphasizes capturing incised flows and spreading water in cascading systems. The goal is to move water across as much of the historical wetland surface as possible and increase infiltration at keypoints. The Keyline Design approach demonstrated at Holman Creek Slope Wetland Complex has contributed the following innovative concepts for the restoration of headwater slope wetlands.

- Implement water-spreading structures that redistribute flow beyond the capacity of the current topography.
- Stabilize erosional features, such as headcuts and incised channels, to become constructed keypoints in the landscape.
- Integrate and expand the wide range of existing techniques to achieve additional functions, such as spreading and splitting water flows.
- Use hedgerow exclosures of native woody vegetation (on contour) as keypoints for water spreading and infiltration.
- Use bank-cut and channel-fill method for spreading water over banks and adjoining wetland patches to immediately aggrade and stabilize small incised channels.
- Use existing infrastructure as keypoints for water spreading and infiltration.

NEED FOR SCIENTIFIC DATA

There is a need for scientific studies and monitoring to quantify benefits of restoration activities using these techniques. Monitoring techniques have been described in a previous technical guide, *Restoration of Slope Wetlands in New Mexico: A Guide for Understanding Slope Wetlands*, *Causes of Degradation and Treatment Options* (2014). Monitoring critical indicators of success and incorporating the conclusions from scientific data will inform the future of innovative restoration techniques. This includes monitoring effects of treatment patterns based on modified Keyline Design principles and the effectiveness and durability of materials used. Monitoring changes in groundwater elevation and flow, local precipitation, water chemistry, wetlands vegetation, soil moisture profiles, wind patterns, solar radiation measurements, and valley-wide cross-section profiles within a wetland complex could add insight for future restoration projects.

FUTURE APPLICATIONS

Use of the Keyline Plow as a Subsoiler for Slope Wetlands

For the purpose of testing Keyline Design for wetland restoration in the Holman Creek Wetland Complex, the restoration team considered testing applications of the keyline plow, but decided to use other techniques for the following reasons:

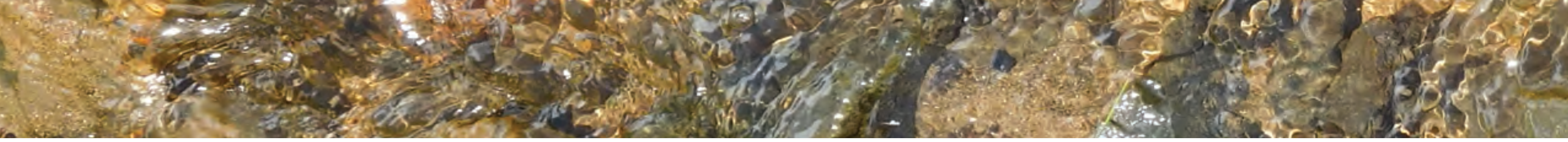
- The slope was fairly steep in many of the headwater wetland valleys. Flat or gently sloping properties better lend themselves to traditional Keyline Design plow patterns - ideally, two percent or less.
- Narrow valley width was a consideration in terms of the space for turning the tractor and plow while minimizing disturbance impacts.
- Substantial micro-topography from erosion and deposition in the wetland valleys over geologic time has created a complicated template for restoration.
- Where wetlands have dried, soils are fine-textured and highly erodible.
- Many ground dwelling mammals live in the valley bottoms.
- The team hypothesized that peat soils in some slope wetland areas in the Holman Creek Wetland Complex (particularly those containing fens) would limit the benefit of using the keyline plow. The keyline furrows might close almost immediately in the highly organic and saturated substrate.
- Fens are delicate and disappearing wetlands in New Mexico and the team did not want to risk damaging them.
- Fens are primarily groundwater dependent; water should never be drained from a fen by diversions.

While there were no identified locations where use of the keyline plow was determined to be appropriate for the Holman Creek Wetland Complex, there are certain wetland site conditions where it might be applied to beneficial effect. For example, use of the subsoiler might work well for wet meadow restoration on relatively flat terrain where there is a water source and appropriate soils and drainage characteristics.

One example is a project on the Coconino National Forest in Arizona (Fig. 5.1). Results from this particular project have not yet been made public. When available, the data will be useful to inform the use of the keyline plow subsoiler for this purpose.

Under very specific conditions, it may be possible and appropriate to use a keyline plow subsoiler in wetland restoration. Such conditions may include the rewetting of former *Juncus*-dominated wetland edges and wet meadows that have dried up due to poor surface and/or subsurface flows or that have formed soil crusts preventing normal infiltration of sheet flows.

Figure 5.1. A restoration project using the keyline plow has been conducted on wet meadow in Long Valley on the Mogollon Rim Ranger District of the Coconino National Forest in Arizona. Linear features are the result of Keyline plow use.

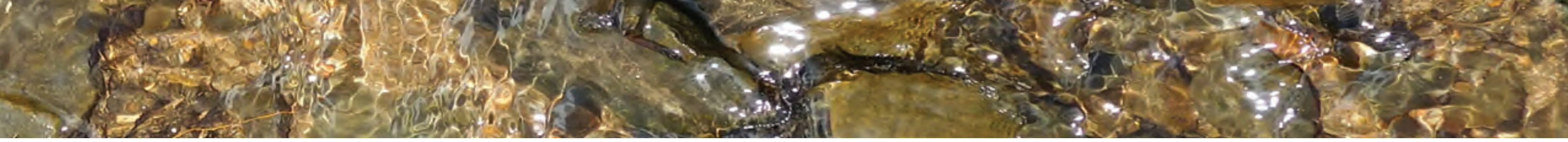


RESTORING WETLANDS IN AGRICULTURAL ENVIRONMENTS

In agricultural environments, irrigation of cultivated plants and ongoing maintenance of irrigation infrastructure are common practices. Under such conditions, traditional Keyline Design strategies could be used for conversion of former wetlands and potential wetlands restoration sites. Diverting water from an upstream tributary to any downstream ones, the use of ponds and reservoirs for water storage, or the Yeomans Keyline plowing method, could be appropriate.

POTENTIAL APPLICATIONS IN SIMILAR WETLAND SYSTEMS

Keyline Design can also be applied appropriately to build treatment trains to rewet areas with upland vegetation that were former wetlands. These techniques lend themselves to rewetting larger areas through prior planning and design. Previous wetlands restoration efforts in the Comanche Creek Watershed stabilized riparian and wetland systems that spread water away from incised channels. The application of Keyline Design encourages restoration practitioners to move water much farther laterally across the landscape. Such distances, greater than have been previously attempted, could potentially distribute water across entire valley bottoms using successive restoration treatments that result in increased wetlands acreages.



REFERENCES

Brinson, M. M. 1993. A hydrogeomorphic classification for wetlands. East Carolina University, Greenville North Carolina.

Brinson, M. M., B. E. Bedford, B. Middleton, and J. T. A. Verhoeven. 2008. Temperate Freshwater Wetlands: Response to Gradients in Moisture Regime, Human Alterations and Economic Status. Pages 127-140 in N. Polunin, editor. Aquatic Ecosystems, Trends and Global Prospects. Cambridge University Press, Cambridge, UK.

Rosgen, D. L. 2011. Natural Channel Design: Fundamental Concepts, Assumptions, and Methods. Pages 69-93 in A. Simon, S. J. Bennett and J. M. Castro, editors. Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, and Tools. Geophysical Monograph Series 194. American Geophysical Union. Washington, D.C.

Winward, A. H. 2000. Monitoring the vegetation resources in riparian areas. Gen. Tech. Rep. RMRSGTR-47. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 49 p.

Yeomans, P.A. 2002. Water for Every Farm: Yeomans Keyline Plan. Keyline Designs. Australia.

Zeedyk, W. D. 2006. A Good Road Lies Easy on the Land: Water Harvesting from Low-Standard Rural Roads. Quivira Coalition. Santa Fe, New Mexico.

Zeedyk, W. D. and V. Clothier. 2014. Second edition. Let the Water do The Work: Induced Meandering, an Evolving Method for Restoring Incised Channels. Chelsea Green Publishing. White River Junction, Vermont.

Zeedyk, W. D., M. Walton and T. E. Gadzia. 2014. Characterization and Restoration of Slope Wetlands in New Mexico: A Guide for Understanding Slope Wetlands: Causes of Degradation and Treatment Options. New Mexico Environment Department, Surface Water Quality Bureau Wetlands Program. Santa Fe, New Mexico.

Zeedyk, W. D. 2015. The Plug and Spread Treatment: Achieving Erosion Control, Soil Health and Biological Diversity. Zeedyk Ecological Consulting, LLC. Sapello, New Mexico.

Zeedyk, W. D. and S. Vrooman. 2017. The Plug and Pond Treatment: Restoring Sheetflow to High Elevation Slope Wetlands in New Mexico. New Mexico Environment Department, Surface Water Quality Bureau Wetlands Program. Santa Fe, New Mexico.