Chapter 5: Meadow Sensitivity to Natural and Anthropogenic Disturbance

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Introduction

Investigations of geomorphic responses to natural and anthropogenic disturbances have revealed marked differences in the rate, magnitude, and nature by which different watersheds, or components of a given watershed, adjust to perturbations. These differences in response are often characterized using the concept of landform sensitivity. The term sensitivity has been defined by different investigators in different ways. For our purposes, it is defined after Brunsden and Thornes (1979) as "the likelihood that a given change in the controls of the system will produce a sensible, recognizable, and persistent response [in the landform of interest]." Inherent in this definition is the tendency for a stream, stream reach, or other landform to respond to an environmental disturbance by going through a period of disequilibrium until a new equilibrium state is achieved (Germanoski and Miller 2004).

Conceptually, sensitivity is thought to involve several distinct components, two of which are (1) the propensity for change as governed by a set of driving and resisting forces, and (2) the capacity of the system to absorb change and remain in an equilibrium state (Downs and Gregory 1993). The rate of change also is important because while a stream or stream reach may be unstable (that is, in a disequilibrium state), it may exhibit a low propensity for change if the driving and resisting forces are such that adjustments occur at a slow rate. Germanoski and Miller (2004) show that for upland watersheds in central Nevada, each of these three components is important. For example, all of the examined basins were found to have incised in response to changes in climate and other perturbations following a major aggradational event between approximately 1980 and 2580 YBP. Watersheds such as Barley (Group 2, table 2.1) quickly adjusted to a new equilibrium state. This process involved rapid incision and profile adjustment with limited influence by side-valley fans. Group 2 channels now possess a low to moderate propensity for change because they have already attained a relatively stable state in comparison to other watersheds in the region. Presumably, they also are better able to absorb the potential effects of future disturbances. Other watersheds also exhibited a low to moderate sensitivity to change (Group 3, table 2.1). However, in contrast to Group 2 basins, the likelihood of change in Group 3 basins is limited by the inability of the driving forces to overcome the forces that resist change at side-valley fans. This is in spite of the stair-step-like nature of the channel's longitudinal profiles (caused by side-valley fans) that place the channels in an inherently unstable condition. Thus, the low to moderate sensitivity of the catchments in Group 3 is based on the very slow rate of change that occurs there.

The concept of sensitivity can be a powerful management tool as it provides insights into (1) the likelihood that a given river or meadow will respond to future disturbances; (2) the timing, duration, rate, and nature of the response; and (3) the potential for a given system to be stabilized or restored (Downs and Gregory 2004; Germanoski and Miller 2004). The concept not only applies to geomorphology but also to system hydrology and biota. In this chapter, we examine the sensitivity of meadow complexes within upland basins of central Nevada in terms of site geomorphology and hydrology.

Geomorphic Sensitivity

Overview

The most important geomorphic processes within meadow ecosystems are incision, gully development and its associated headcut migration, groundwater sapping, and avulsion (Chapter 3). The rate, magnitude, and frequency of these processes are governed by numerous factors that must be considered in the analysis of meadow sensitivity to disturbance. Quantification of the combined effects of these processes for the purposes of creating predictive models of meadow sensitivity is a complicated and difficult task that must be undertaken on a meadow-by-meadow basis. These complications result from the following factors:

(1) The parameters that control meadow sensitivity function over different temporal and spatial scales. Incision, for instance, is closely tied to both sediment supply and the ability of flood flows to entrain and transport sediment. Thus, the geomorphic sensitivity of a meadow is closely related to the magnitude of runoff for a given frequency of event. The magnitude of runoff is associated with the amount and rate at which water can be funneled through the drainage network to a meadow and is influenced by factors like upstream basin area, relief, absolute elevation, ruggedness, drainage density, geology, and vegetation cover. If no other controls were present, meadow sensitivity would likely decrease from Group 1 to Group 5 (table 2.1) and could be fully characterized by basin morphometry and its effects on precipitation-runoff relations. However, local factors including channel gradients, valley slope and widths, and localized groundwater discharge via springs and bank seepage may either increase or decrease the geomorphic sensitivity of meadows (see

Chapters 3 and 4 for a discussion of the parameters that control these factors). Quantification of meadow sensitivity therefore requires the integration of processes that operate over spatial scales ranging from the entire basin to a channel cross section, a process that is conceptually and mathematically challenging.

(2) Sensitivity is controlled by the interaction of multiple reach-scale parameters that produce non-linear variations in process rates. Moreover, an increase or decrease in one variable may or may not have a strong influence on meadow sensitivity, depending on the nature of other parameters. Take, for instance, channel slope. A 2 percent increase in slope immediately downstream of a meadow (as is commonly found) tends to promote channel incision because higher gradients increase the erosive capability of flood flows, provided the other controlling factors are equal. However, in addition to slope, meadow sensitivity depends on such factors as bed material size and composition, water availability, and the frequency and magnitude of runoff events. Thus, meadow sensitivity cannot be determined on the basis of a single parameter, such as slope, but must include an analysis of multiple parameters and their interactions.

(3) Geomorphic processes that are of most importance in dictating meadow sensitivity are controlled by multiple mechanisms of landform change, which vary spatially over the meadow complex. For example, incision typically involves the grain-by-grain entrainment and transport of sediment as well as the development and migration of knickpoints or headcuts. The rate, magnitude, and nature of these processes vary along the meadows, in part, as a function of the underlying composition of the valley fill. Thus, quantitative predictions of future incision require detailed analyses of both mechanisms of incision and their interactions for a given material type, a particularly difficult task given that the sediments that underly meadows often change unpredictably.

(4) Meadows are subjected to abrupt shifts through time in the predominant geomorphic processes operating at the site. These process shifts cannot be easily predicted and are dependent on the timing and frequency of major hydrologic events. For example, unincised valley floors were observed to be initially dissected by the erosion of individual particles. As gully depth increased, there was often an abrupt change in the mechanism of incision from the entrainment of individual clasts to one of headcut migration controlled by groundwater-influenced, mass wasting processes. Additional shifts in process occurred during extreme flood events as groundwater-controlled headcut advancement was overridden by plunge pool development, headcut undermining and failure, and sediment removal by surface flows.

Given the above considerations, a *quantitative* assessment of meadow sensitivity to geomorphic change is challenging and requires a detailed analysis of the meadow system. However, as pointed out by Pilkey and Pilkey-Jarvis (2007), a *qualitative* understanding of the physical processes that are operating in a system often can be used to more effectively develop sound management strategies than quantitative models that may dramatically simplify the system or represent outliers of developed empirical trends.

Here, we highlight the primary factors that control meadow sensitivity and how a qualitative analysis of those factors (summarized in fig. 5.1 and table 5.1) can be used to predict the overall geomorphic sensitivity of meadows. The intent is not to develop a system that can replace the need for detailed geomorphic, hydrologic, or biotic analyses of a site. Rather, the goal is to provide a checklist of parameters that

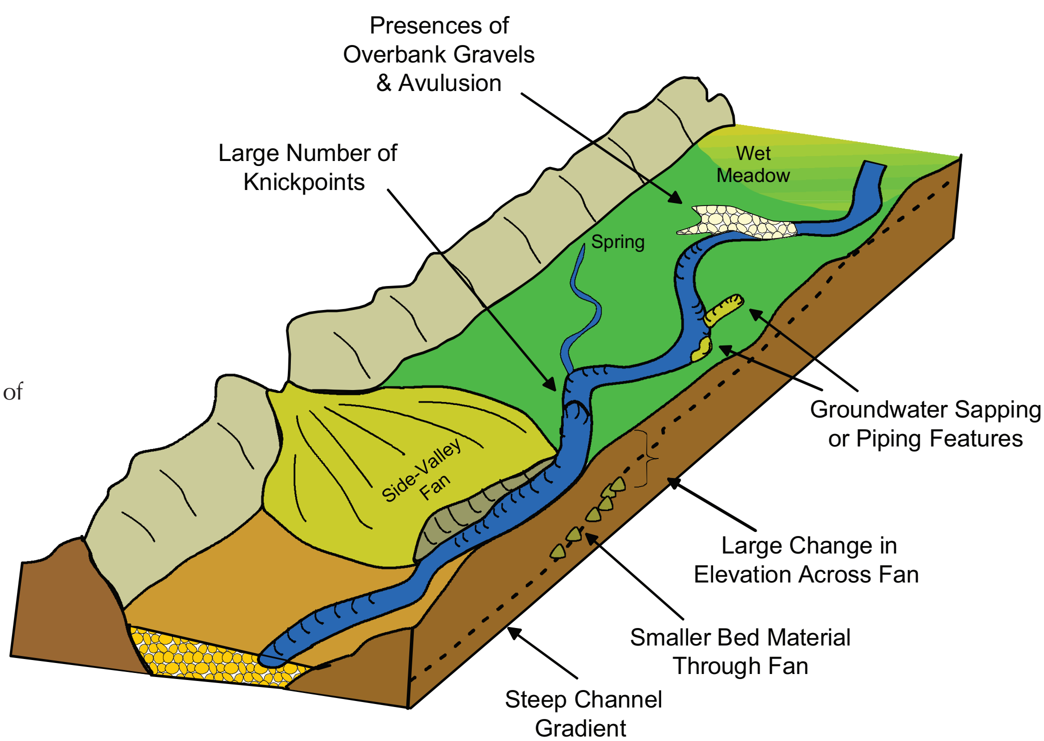

Figure 5.1. Factors that influence the geomorphic sensitivity of meadow complexes.

Table 5.1. Factors influencing the geomorphic sensitivity of meadow systems.

Factors	Factors Contributing to Sensitive Meadows
Sensitivity to incision, headcut migration, and groundwater sapping	
Water availability	
–Basin characteristics	Large basins, high relief, significant catchment area at high elevations (>3000 m), high ruggedness numbers and drainage densities, impermeable geological materials such as volcanic rocks
–Groundwater discharge	Numerous, high discharge springs feeding spring channels; upward flow gradients and artesian conditions
Flow convergence	
–Valley width	Narrow valleys that abruptly decrease in width down-valley causing groundwater and surface water convergence
–Anthropogenic structures	Berms, dams, and other features that may lead to highly concentrated (channelized) flow on meadow surface
–Linear features	Cattle trails, roads, and other linear features that are devoid of vegetation and may capture and concentrate runoff
Gradients	
–Profile convexities	Occurrence of large convexities in long profile, which cause channel instabilities
–Channel/valley floor	Abrupt increases in channel or valley gradient, particularly through side-valley fans or other profile convexities
Composition of valley fill	
–Channel	Decrease in size of the channel bed material; an exception is the occurrence of highly resistant, clay-rich units commonly associated with paleosols
–Undissected valley floors	Valley fill composed of coarse sand and granules (grus) commonly associated with quartz monzonites and diorites; highly susceptible to erosion and groundwater sapping during rare, high-magnitude runoff events
Knickpoints/headcuts	
–Occurrence	Frequent knickpoints or headcuts, particularly within meadow
–Advancement mechanism	Knickpoints or headcuts advancing by plunge-pool formation, undermining, and failure (most sensitive); groundwater driven mass wasting; sapping (seepage erosion), especially where valley fill is highly permeable
–Surface flow	High probability of receiving surface flows; headcuts fed by shallow channels, roads, cattle trails, or other flow concentrators
–Groundwater; seepage	Higher water tables and pore pressures; layered stratigraphy containing units of highly contrasting permeabilities
–Material composition	Sandy units with higher rates of headcut retreat; clay-rich units sensitive to groundwater piping and locally extensive surface incision of meadows

Table 5.1. *Continued.*

Factors	Factors Contributing to Sensitive Meadows
Sensitivity to avulsion	
Sediment availability	
–Geomorphic instabilities	Numerous zones of upstream sediment influx to channel, including areas of mass wasting on hillslopes or trenching of side-valley fans
–Beaver dams	Numerous beaver dams, storage of large volumes of coarse (gravel-sized) sediment
–Anthropogenic features	Anthropogenic features such as roads that may supply and funnel large volumes of sediment to channel; physical connectivity to channel is very important to sediment delivery
Gradients/transport capability	Low-gradient zones, particularly where gradients decrease abruptly or where loss of water results in a loss of flow competence
Channel depths	Shallow channels or zones characterized by distributary network as upstream channels enter meadows
Resistance to flow (roughness)	
–Vegetation	Increases in roughness associated with riparian or in-channel vegetation, particularly willows
–Structures	Downstream increases in roughness associated with the construction of in-stream structures or other features
Spring channels	Increases in frequency of spring channels which may capture overbank flood waters and promote channel capture

can be rapidly evaluated by land managers to identify the sensitivity of meadows that may or may not be suitable for treatments aimed at reducing the magnitude or rate at which a given geomorphic process negatively impacts a meadow. Those meadows where mitigating the impacts of geomorphic processes appears plausible in terms of their sensitivity to change will require more detailed assessments prior to the selection and implementation of any physical treatment method (e.g., the installation of in-stream structures, bank protection devices, or channel reconstructions).

Geomorphic Sensitivity to Incision

Longitudinal profiles along trunk valleys of upland watersheds show that axial streams possess a stair-step-like morphology in which low-gradient reaches form the step tread and high-gradient reaches form the riser (fig. 5.2). Meadows are frequently located along the low-gradient reaches or tread of these topographic steps (figs. 5.2). These steps or convexities in the profile form zones of instability that are prone to incision or gully development (Chapter 3). If a convexity exists, the meadow will likely incise at some time in the future. The potential magnitude of incision is dictated by the size (height) of the convexity, which is defined by the difference in elevation between the channel bed (or valley floor) and a uniformly sloping profile that is projected along the upstream channel bed (or valley floor) through the convexity at the downstream terminus (fig. 5.2). However, the existence of a convexity, even one of considerable size, does not necessarily guarantee that a meadow is highly sensitive with respect to channel bed lowering or meadow dissection. The typical runoff event may not be capable of entraining and transporting the material found along the channel bed, thereby inhibiting incision with small to moderate runoff events. In fact, the existence of the stepped profile indicates that incision has not occurred at a rapid rate

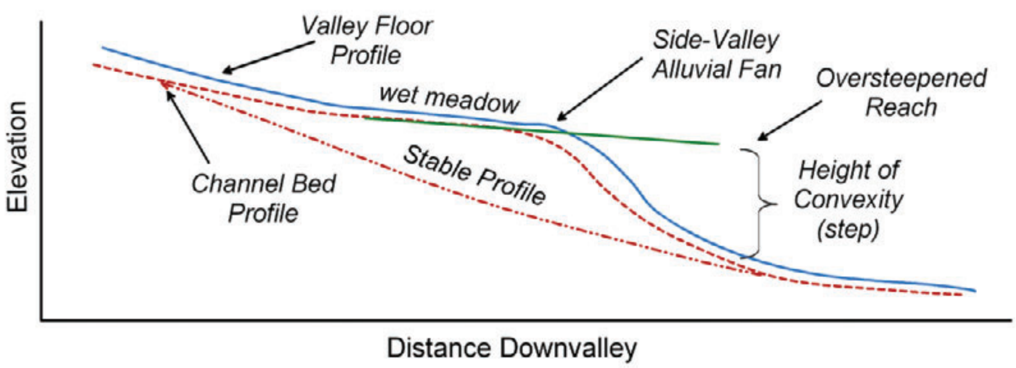

Figure 5.2. Topographic convexity and definition of step height.

during approximately the past two millennia, at least where channel profiles are influenced by sediments deposited at the mouth of tributaries (Miller and others 2004). Thus, meadow sensitivity with respect to incision is strongly controlled by the magnitude and frequency of flood flows that are capable of eroding channel bed material, thereby elevating the stepped profile.

Incision is promoted by the ability of a basin to collect and effectively funnel water to meadows. Factors that influence the erosive capability of runoff events include basin elevation and the amount of snowpack accumulation in upland areas, and basin morphometric parameters such as size, relief, and ruggedness upstream of the meadow (Germanoski and Miller 2004). Once runoff water reaches the meadows, the erosive ability of water is modified by local conditions. Thus, while an abundant supply of water may be required for incision, it does not automatically indicate that incision will occur. Local factors that promote incision are: (1) narrow valleys that concentrate overland flood flows; (2) extensive subsurface discharge via springs and bank seepage; and (3) steep channel gradients, both within the meadow and along stream segments that are located immediately downstream of the meadow (Chapter 3). Incision along the downstream reach is important because lowering of the channel's base level in these areas tends to produce localized incision that propagates upstream through the meadow complex (Chapter 3). The rate of incision, and therefore meadow sensitivity, also is strongly influenced by size of the channel bed material, which must be entrained and transported downstream. Put differently, it is influenced by the resistance of the channel bed to erosion.

The traditional and most widely used approach to assessing particle motion and, therefore, the potential for incision is based on the Shields (1936) criterion. The Shields criterion was developed using flume data and evaluates the shear stress near the channel bed that is required to get a particle into motion by moving it up and over its downstream neighbor. The method was constructed for particles of uniform size and yielded the expression:

$$\tau_c = \rho d_w S = 0.06\,(\rho\text{-}\rho_s)gD \qquad (5.1)$$

where τ_c is the critical shear stress at which particle motion begins; ρ and ρ_s are the densities of the fluid and particle, respectively; *g* is the gravitational constant; *S* is the slope of the water surface; and *D* is the diameter of the particle of interest (which is assumed to be similar to the surrounding particles).

More recent studies have shown that the Shields criterion is valid only for channels where the bed material is of nearly uniform size (Reid and Dunne 1996). In the case of gravel-bed rivers where bed sediment may range from sand to boulders, the equation requires modification for several reasons. First, larger, surrounding neighbors hide or protect smaller particles from the flow. These smaller particles require higher shear stresses than predicted by the original Shields equation in order to initiate motion. In contrast, particles that are larger than average project above surrounding clasts, are readily exposed to the flow, and require lower shear stresses for particle motion than predicted for uniform grains. Other factors of importance to gravel-bed rivers are the binding together of particles of differing size and shapes as they are packed into the stream bed, formation of bedforms, and development of vertical layers of differing grain size distributions in the channel bed (e.g., pavements and subpavements). At present, there is no consensus as to the degree of reduction in shear stress that occurs in gravel-bed rivers (or streams) (Reid and Dunne 1996). A wide range of equations has been developed to describe the initial motion of large particles (table 5.2). The differences among these equations are partly related to differences in the datasets used to create them and the definitions of initiation of motion and shear stress (Reid and Dunne 1996).

One way of using the equations (table 5.2) to assess the probability of incision is to estimate the percent of the channel bed that is likely to be mobilized at a given shear stress. The shear stress required to transport particles that comprise different percentages of the pavement can be calculated using the various equations shown in table 5.2 and plotted in figure 5.3 for the Snoqualmie River, Washington (which has median particle sizes of 56 and 17 mm in the pavement and subpavement, respectively) (Reid and Dunne 1996). These curves can then be compared to the shear stresses that are likely for varying flow depths within the channel. Changes in shear stress as a function of flow depth can be easily estimated using the equation:

$$\tau = \gamma RS \qquad (5.2)$$

where γ is the specific weight of the fluid, *R* is the hydraulic radius of the channel, and *S* is the slope of the water surface. An advantage of this simplified approach is that data required for these calculations can be easily collected during a single visit to the site.

Given the approximate nature of the estimates of shear stress required to initiate motion by the equations in table 5.2, predictions of particle entrainment and the potential for channel bed incision must be used with a strong degree of skepticism. The probability of incision is further complicated by the presence and advancement of knickpoints. Nevertheless, this approach (which determines the likelihood for particle entrainment for a given set of flow conditions will provide valuable insight into whether the bed material exhibits a low, moderate, or high degree of mobility. It may be particularly useful to apply these equations to large clasts found along the relatively high-gradient reaches of the channel steps to determine if particle entrainment of the materials controlling the local base level is likely.

Assessment of meadow sensitivity to incision by means of knickpoint or headcut migration is a more difficult task. Meadow development is highly variable from basin to basin and depends on both surface and groundwater conditions. The spatial distribution of headcuts shows that they tend to develop in areas of steep valley gradients, abundant water, and concentrated flow. These parameters often coincide along reaches of the valley floor that are prone to incise by means of knickpoint or headcut advancement. For example, many meadows occur on wide segments of the valley that

Table 5.2. Selected equations used to predict the initiation of motion. Critical shear stress (τ_c in dynes/cm^2) is calculated for individual particles of size D_i (cm) positioned within the channel bed material with a median grain diameter (D_{50}, in cm) for geometric mean diameter (D_g, in cm). Modified from Reid and Dunne (1996).

Reference	Equation	Definition of Motion[1]
Shields (1936)	$\tau_c = 0.056\ (\rho_s\text{-}\rho)gD_i$	
Miller and others (1977)	$\tau_c = 0.045\ (\rho_s\text{-}\rho)gD_i$	
Parker and others (1982)	$\tau_c = 0.09\ (\rho_s\text{-}\rho)gD_{50}$	Bedload
Diplas (1987)	$\tau_c = 0.087\ (\rho_s\text{-}\rho)gD_i^{0.06}D_{50}^{0.94}$	Bedload
Parker (1990)2	$\tau_c = \tau_{rg}\ (\rho_s\text{-}\rho)gD_i^{0.10}D_{50}^{0.90}$	Bedload
Komar (1987)3	$\tau_c = 0.045\ (\rho_s\text{-}\rho)gD_i^{0.35}D_{50}^{0.65}$	Clast
Andrews (1983)	$\tau_c = 0.083\ (\rho_s\text{-}\rho)gD_i^{0.13}D_{50}^{0.87}$	Clast
Ashworth and Ferguson (1989)	$\tau_c = 0.072\ (\rho_s\text{-}\rho)gD_i^{0.35}D_{50}^{0.65}$ $\tau_c = 0.054\ (\rho_s\text{-}\rho)gD_i^{0.33}D_{50}^{0.67}$ $\tau_c = 0.087\ (\rho_s\text{-}\rho)gD_i^{0.08}D_{50}^{0.92}$	Bedload Bedload Bedload
Komar and Carling (1991)	$\tau_c = 0.059\ (\rho_s\text{-}\rho)gD_i^{0.36}D_{50}^{0.64}$ $\tau_c = 0.039\ (\rho_s\text{-}\rho)gD_i^{0.13}D_{50}^{0.82}$	Clast Clast
Costa (1983)	$\tau_c = 26.6D_i^{1.21}$	Deposit
Williams (1983)	$\tau_c = 12.9D_i^{1.34}$	Deposit

[1] Method with which particle motion is defined; Bedload—initiation of motion defined by occurrence of a small but finite amount of transport; Clast—initiation of motion defined by largest particle moving at a given τ; Deposit—initiation of motion defined from the largest particles deposited during an event with a given τ at crest stage.

[2] D_g is the surface geometric mean diameter of the clast, which is calculated as $\ln D_g = \Sigma F_i \mathrm{Ln} D_i$, where Fi is the ith particles size class and has a geometric mean of D_i, and $\tau_{rg} = 0.836(D_g/D_{50}\mathrm{sub})\text{-}0.905$ is the reference dimensionless shear stress for D_g.

[3] Equation based on surface grain parameter but used for subsurface.

are characterized by low gradients (Chapter 3). During flood events, overland flows are concentrated by a reduction in valley width and are augmented by groundwater discharge. In addition, the erosive capability of the flow is enhanced by increases in gradient, thereby creating the ideal situation for gully/headcut formation. Once produced, the headcuts have the potential to migrate upvalley into the meadow system. Thus, variations in valley width, gradients, and zones of groundwater discharge are important factors that influence the degree of channel incision within the meadows.

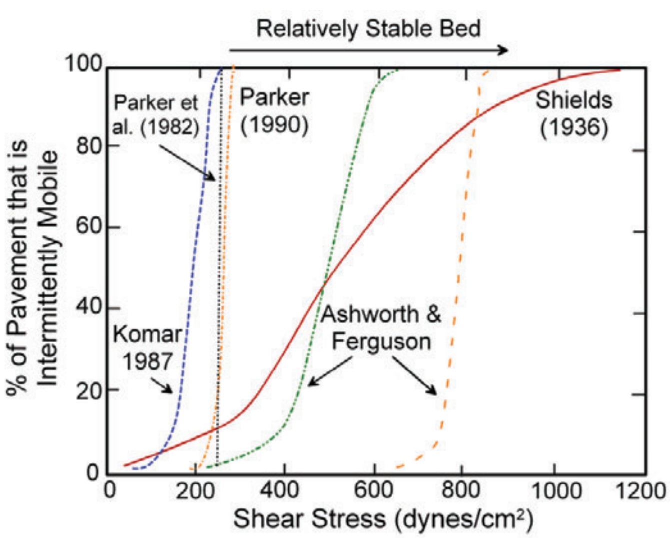

Figure. 5.3. Percent of channel bed clasts that are mobile, as calculated using equations in table 5.2. Data for Snoqualmie River, Washington. Figure from Reid and Dunne (1996).

The existence of a knickpoint or headcut indicates that the channel or valley floor is unstable and subject to entrenchment. However, a knickpoint or headcut does not necessarily mean that the meadow is highly sensitive to incision as these features may not migrate upstream at a significant rate (that is, within 10^0 to 10^2 years). Insights concerning the rates of knickpoint or headcut migration into and/or through a meadow can be obtained by examining (1) the source and availability of water to the feature and (2) the processes through which the features advance upvalley (Chapter 3). For knickpoints within a well-defined channel of a meadow complex, field surveys demonstrated that the primary mechanism of advancement is by means of knickpoint retreat associated with plunge pool formation, material undercutting, and failure of the knickpoint face. When combined with a concentrated and continuous supply of water from upstream, the knickpoints generally move quickly through the meadow (as in the case of Kingston 3 meadow, Chapter 3) unless migration is hindered by dense resistant roots, such as those associated with willows (as is the case in Birch Creek; fig. 1.7). Thus, where these types of knickpoints exist, meadows are moderately to highly sensitive to incision through continued knickpoint migration.

Rates of headcut migration into previously undissected meadows are more variable, both between meadows and through time at a given meadow. Although quantitative data on rates of migration are limited, they range from a less than 1 m per year to tens of meters per year during high magnitude events such as occurred in 1982 and 1983. In general, headcut retreat that is driven by seepage erosion or groundwater-related mass wasting processes (as observed in Indian Valley and Corcoran Canyon, fig. 1.7) proceeds rather slowly—less than approximately 1 m per year. These rates are unlikely to change significantly from one runoff year to the next if the available surface water is limited due to a small upstream catchment area of low relief or altitude or a wide valley that is incapable of concentrating flow. For example, in Cahill Canyon (fig. 1.7), a low-relief headcut is advancing into a small meadow located near the headwaters of the drainage. Although the headcut is positioned along a slightly oversteepened reach of the valley floor and is developed in fine-grained sediments, the likelihood of rapid advancement is small because both surface and groundwater flow to the headcut is limited. In contrast, headcut advancement by means of plunge pool development and failure associated with overland flows can occur much more rapidly. In Indian Valley, for example, the diversion and concentration of flow onto a previously undissected portion of the valley floor led to extremely high rates of upstream headcut migration—several to tens of meters per year—between 1961 and 1982 (fig. 3.15).

The mechanisms of headcut migration can change through time. Temporal changes are associated with rare, high magnitude runoff events and anthropogenic activities that concentrate flow on the valley floor; remove the existing vegetation; and, reduce the erosive resistance of the valley fill. Examples of anthropogenic activities include development of roads, drainage diversions, or berms. Livestock, which often produce trails capable of concentrating flow and funneling it to the top of headcuts, may also exacerbate upvalley headcut migration (for example, Indian Valley, fig. 3.19).

A rapid and effective method of assessing meadow sensitivity to headcut advancement is to determine the rates of upstream headcut migration by comparing the position of headcuts on aerial photographs of differing ages. If multiple sets of photos are examined, the average rates of migration can be determined for the period bracketed by the aerial photographs. The estimated rates, determined for multiple photographic pairs, can then be compared to local precipitation records to determine rates of advancement associated with the period's precipitation/runoff magnitudes. In addition, it may be possible to obtain a qualitative understanding of the frequency with which flood flows cause rapid upstream headcut migration. The analysis also can provide insight into the portions of the meadow that may be sensitive to current or future incision by headcut migration and into the causes of instability such as diversion of surface flows to a new area of the meadow or valley floor.

Meadows that are extremely sensitive to incision by groundwater sapping processes are those that are underlain by highly permeable sediments such as the grus-dominated valley fill in Marshall Canyon. Erosion of small, discontinuous channels during low to moderate runoff events may lead to a shift in the dominate erosion process to groundwater sapping during major floods, particularly where flows from tributaries and springs converge. As a result, headcuts can form and migrate tens of meters in a few days (fig. 3.7), making these meadows extremely sensitive to disturbance (see discussion on Marshall Canyon, Chapter 3).

Geomorphic Sensitivity to Avulsion

The geomorphic processes that affect wet meadow ecosystems are incision, localized aggradation, and avulsion (Chapter 3). Avulsion events can significantly alter meadow complexes by (1) delivering coarse gravel-sized materials to the valley floor; (2) creating high, linear ridges within the meadow that exhibit relatively deep water tables; and (3) leading to development and enlargement of new channels, which are often prone to incision and localized groundwater lowering (fig. 3.22).

Avulsion is caused by the interaction of several factors that lead to a threshold crossing event. While it is extremely difficult to predict the probability that a meadow will experience an avulsion during a given period, the primary controlling factors can be evaluated to assess whether a meadow has a high, moderate, or low risk of channel shifting and abandonment. For example, avulsion within a meadow is primarily driven by the rapid influx or release of coarse sediment from an upstream reach and the subsequent deposition of that sediment within the channel as it traverses the meadow complex. Thus, the likelihood of avulsion is closely tied to upstream sediment sources, which may periodically deliver large quantities of coarse material to the drainage network. Without these sources and the influx of coarse sediment, avulsion will not occur. Thus, any evaluation of the future stability of a meadow should involve the identification of upstream sediment supplies. Potential supplies are: (1) beaver dams and ponds that store large volumes of course debris that can be released upon dam failure; (2) unstable hillslopes that are characterized by mass wasting scars, which can deliver sediment directly to the channel; (3) steep roads that cross or lie immediately adjacent to the channel and have the potential to be extensively gullied; and (4) steep side-valley alluvial fans that are or may become trenched, thereby supplying sediment to the drainage system. Each of these sources can be mapped on topographic sheets, and their potential to supply debris to the drainage network can be evaluated.

The influx of coarse sediment to the channel does not always lead to avulsion as the material may be transported downstream through the meadow complex. It is therefore necessary to examine the local factors that may lead to avulsion within the meadow. One factor that promotes avulsion is a reduction in the capacity of the channel to contain moderate to large flood events. Decreases in channel capacity are frequently related to stream bed aggradation produced by a decline in channel gradient near upstream meadow segments. Reductions in stream gradients are common (fig. 3.21) and result in a lowering of both channel capacity and competence. Other factors that lead to aggradation are an increase in roughness (resistance to flow) caused by riparian vegetation, particularly willows, and in-stream obstructions to flow, including erosion control structures.

Ongoing stream aggradation can be identified along meadow channels in the form of longitudinal bars on terraces and other low-lying surfaces next to the stream (fig. 3.21) or as thick accumulations of gravel within the channel bed, which are often accompanied by reductions in channel depth. Whether or not these zones of aggradation ultimately result in avulsion depends on the loss in channel capacity and depth and the nature of adjacent meadow topography. In a review of the causes of avulsion, Jones and Schumm (1999) found that avulsion was promoted by steep floodplain gradients in comparison to the pre-avulsion channel. In central Nevada, meadow surfaces are most likely to exhibit gradients that are greater than those of the channel in areas where the stream is highly sinuous. Highly sinuous channels exhibit a higher likelihood of avulsion than straight channels, provided other controlling factors are similar. Another control on the likelihood for avulsion is the occurrence of linear depressions, which are often associated with paleochannels within the meadow complex. These depressions may be intersected by the modern channel. Where they intersect, channel depths and, therefore, capacities are relatively low, allowing flood waters to spill over into the depression before inundating other portions of the meadow's surface. Spring channels also serve as preferential routes of flood flow. The fine-grained nature of sediments at the surface of depressions and lining the perimeter of spring channels often allows them to be scoured, producing topographic conduits with a bed below the adjacent channel floor. As a result of the differing channel bed elevations, the newly scoured channel can eventually capture the entire upstream flow. For example, in the Birch Creek 1 meadow (fig. 1.7), aggradation and a loss in channel capacity presumably led to a recent increase in overbank flooding. The flood flows were concentrated in the spring channel, which over time incised and widened to become the new truck channel, leaving the aggraded reach as an abandoned segment. Localized aggradation of an unincised reach farther upstream and subsequent willow colonization suggests that the meadow remains highly sensitive to avulsion processes because (1) channel capacity is likely to be decreased by the deposition of coarse-sediment within the channel, resulting in overbank flows, and (2) the overbank flows may be routed into existing spring channels.

Man-made structures often increase hydraulic roughness and can, therefore, lead to stream bed aggradation and a loss in channel capacity if there is a supply of coarse sediment to the reach. If the loss in channel capacity is significant, the result may be avulsion. Thus, care must be taken to ensure that structures that are used to inhibit channel incision while coarse sediment influx is limited do not lead to aggradation and avulsion during large events when bedload transport rates are high. In other words, in-stream structures or other forms of bed and bank modifications may simply shift the zone of incision to a new location. Possible approaches to limit the effects of these structures are to design structures to fail during high magnitude events, thereby reducing their ability to cause intense, localized aggradation, and to restrict their use where coarse sediment is likely to be input to the meadow.

Geomorphic Sensitivity Summary

Numerous factors promote and resist geomorphic change within meadow complexes (table 5.1). The challenge for land managers is to determine whether interactions of these factors at a particular meadow have produced a system that is relatively stable and has the potential to be effectively managed or a system that is highly sensitive to change. Determining outcomes of interacting factors is difficult. Nevertheless, an evaluation of whether the factors (table 5.1) contribute to meadows of high, moderate, or low sensitivity informs the likelihood of future change. Take, for example, a meadow characterized by a large, upstream basin; a rapidly narrowing downstream valley; and a channel that is characterized by a pronounced convexity, steep downstream gradients, relatively small bed material, and significant groundwater influx. The combined effects of these factors will likely produce a meadow that is highly sensitive to geomorphic change. Thus, a simple checklist evaluation of the primary controlling factors can be used to rank the sensitivity of upland meadows to incision or avulsion. This evaluation can be used to decide if it is necessary to conduct more detailed geomorphic studies of the site with the intent of developing management options or if resources would be more wisely spent on another meadow system.

Hydrologic Sensitivity

Overview

The concept of hydrologic sensitivity of meadows is used here in a manner similar to geomorphic sensitivity. Hydrologic sensitivity describes the propensity for changes in groundwater conditions that result in a decline in the water table depth. Because montane meadow complexes in the central Great Basin are groundwater-dependent ecosystems, the typical response is a shift in vegetation patterns from wet and mesic meadow community types to drier types over part or all of the meadow (Chambers and others 2004). The drivers of change within meadows, in most cases, are related to the processes of channel incision, headcut migration, or avulsion. Drivers of change external to meadows include climatic change and disruption of recharge, routing, or connectivity of source waters that support meadows.

The general relationship between stream incision, lowering of the water table, and vegetation shifts have been described for arid and semi-arid regions (Stromberg and others 1996; Chambers and Miller 2004; Webb and Leake 2006). In some studies, linkages between streams, groundwater levels, and vegetation have been well enough established to develop models to predict vegetation shifts in response to changes in hydrology (Schilling and others 2004; Loheide and Gorelick 2007). However, in many places, hydrogeologic complexity prevents effective use of quantitative models. Variables that limit the value of quantitative models include lack of stratigraphic data, partial penetration of streams into aquifers, transient hydrologic conditions, and characterization of stream bed materials related to exchange of groundwater and stream water (Woessner 2000; Sophocleous 2002; Vidon and Hill 2004; Loheide and others 2009). In some cases, such as in major restoration projects, money- and time-intensive efforts may be warranted to fully evaluate meadow conditions in order to develop accurate quantitative models. However, for most areas, these intensive efforts are seldom feasible. Alternatively, conceptual models based on a process-based understanding can be effective research and management tools (Woessner 2000; Vidon and Hill 2004; Loheide and others 2009).

Hydrologic Processes and the Factors Controlling Sensitivity

Our study of 56 riparian meadows has provided information on meadow processes, linkages between biotic and abiotic systems, and landscape controls. In this section, qualitative factors controlling hydrologic sensitivity are used to assess meadow conditions. The key controls on hydrologic sensitivity are: (1) based on conceptual models that have been validated through our research, (2) observed in other riparian systems, and (3) founded on established principles of hydrogeology.

The individual hydrologic characteristics of meadows are wide ranging, but sufficient generalizations can be made to provide a foundation for analyzing hydrologic sensitivity. Springs, artesian conditions, and perched water tables in meadows of the central Great Basin indicate the presence of heterogeneous geologic materials and complex groundwater conditions. The typical meadow has a complex geologic setting with complex stratigraphy characterized by strongly contrasting hydraulic conductivities and high hydraulic gradients. The variability in spatial and temporal hydrologic patterns, such as water levels and pathways, also is due to natural climate and weather cycles and the combined influences of mixed groundwater sources. The nature of the connection between groundwater and surface water (Chapter 4) is an especially strong determinant in how the water table and, therefore, vegetation types respond to stream incision. Different parts of meadows have different hydrologic patterns, and changes that are external to the meadow in the recharge regions of the source waters also affect meadow hydrology. Thus, evaluation of meadow sensitivity requires an understanding of each meadow's hydrologic, geomorphic, and vegetation characteristics.

Four groups of factors are used to assess hydrologic sensitivity: (1) meadow hydrology, including groundwater and stream water interactions; (2) meadow stratigraphy; (3) geomorphic processes and stratigraphic setting; and (4) source waters (table 5.3).

Meadow Hydrology: Groundwater-Stream Water Interactions

The connection of surface water to groundwater along stream channels is recognized for its importance in nutrient transfer and other aspects of stream ecology (e.g., Hayashi and Rosenberry 2002; Sophocleous 2002). The term "connection" is used to describe if and how often stream water is connected to groundwater along the channel perimeter. The type and nature of the channel connection to the groundwater table directly affects the kind and magnitude of groundwater responses (table 5.3a.1; fig. 5.4). Several connection types are recognized: (1) continuous, which requires perennial stream flow and a shallow water table; (2) intermittent or ephemeral, where stream flow or seasonal variations in water table elevation are needed for a connection; and (3) not connected under typical climatic conditions, where stream flows are short-lived and groundwater tables are deep (e.g., Lerner 2003). The connection type does not indicate directly whether the stream segment is gaining or losing.

Channels that are created and fed only by springs, not runoff, tend to be small and do not significantly disrupt the water table geometry (fig. 5.4a). Spring-fed channels tend to have lower width to depth ratios and less variable discharge than runoff-dominated channels (Griffiths and others 2008). Channels that convey runoff are larger and, in general, much more dynamic than spring-fed channels. In some places, channels that convey runoff are perennial, whereas in others, they are ephemeral or intermittent, flowing only during periods of high runoff. Perennial channels that convey runoff and groundwater baseflow intersect the water table, are typically gaining, and cause subsurface flow convergence that results in a lower water table adjacent to the channel (fig. 5.4c). Stream incision of these channels causes further declines in the water table and, consequently, can lead to shifts in plant community types. This response is well documented (see Chambers and others 2004; Shilling and others 2004; Loheide and Gorelick 2007; Loheide and others 2009). Intermittent and ephemeral runoff channels are not connected to the water table for most of the year, and when they do convey flow, they are losing stream segments (fig. 5.4b). Incision of these channels will not cause a decline in the water table unless the channel reaches a depth where it intersects the water table.

Perennial channels that convey runoff are typically gaining streams. However, some of the perennial stream segments in meadows are losing, even though they are connected to the groundwater and convey some runoff (table 5.3a.2). These stream segments can support meadow complexes as indicated by the occurrence of wet or mesic plant communities adjacent to the channel and drier plant communities at distance from the channel (fig. 5.5). Where streams are the primary source of water to meadows, stream incision has the potential to cause a complete loss of shallow groundwater necessary to support wet and mesic vegetation.

Table 5.3. Factors influencing the hydrologic sensitivity of meadow systems.

Factors	Factors Contributing to High Sensitivity of Meadows
A. Sensitivity related to meadow hydrology: groundwater-stream water interaction	
(1) Stream channel connection to groundwater fig. 5.4	Stream channels that intersect groundwater table and are incised deeply enough to cause groundwater flow convergence to channel, typically reflected by vegetation patterns adjacent to channel
(2) Gaining or losing fig. 5.5	Losing streams that are primary water source for meadows, especially in perched systems, because further incision will increase depth of groundwater table in wettest part of meadow and may cut off recharge of shallow, perched system
(3) Relation of groundwater flow direction to position of new channel fig. 5.6	Incision of valley floor on upgradient side of flow will cause drop in groundwater table across remainder of valley floor.
B. Sensitivity related to meadow stratigraphy	
(1) Hydraulic conductivity of meadow sediments adjacent to stream channel fig. 5.7	Incision of high hydraulic conductivity materials will cause more of a widespread drop in the water table than finer-grained materials.
(2) Key hydrostratigraphic units and stratigraphic complexity figs. 5.8 and 5.9	Areas with complex stratigraphy, especially with perched and artesian conditions, are most likely to change significantly (unpredictably) with incision or new channels. In extreme cases, incision of a key confining layer may cause widespread drop in water table and loss of entire wet meadow complex.
(3) Resistance of stratigraphic units to erosion fig. 5.10	Pervasive fine-grained, noncohesive sediments are more prone to erosion, causing lowering of water table
C. Sensitivity related to geomorphic processes and stratigraphic setting	
Hydrogeomorphic condition after incision or new channels fig. 5.11	Incision or new channels that do not create new, lower-elevation meadow complexes result in a greater net loss of meadow area.
D. Sensitivity related to source waters	
Source waters and their connectivity to meadows figs. 5.12 and 3.18	Meadows supported by source waters with limited recharge areas, a limited recharge period, and variable connectivity to the meadow hydrology are susceptible to change due to upland changes in land cover, climate, and stream channels.

The sensitivity of this type of system is well documented in meadows 1 through 5 in Corcoran Canyon (figs. 1.7 and 4.2), which occur on step-shaped profiles. The string of five meadows are separated by non-meadow zones, where the stream channel is incised to depths greater than 0.5 m (table 4.2d).

The hydrologic sensitivity of a meadow can be directly influenced by the geomorphic sensitivity, especially when new channels are formed, such as by headcut migration or avulsion. The locations of new channels with respect to the direction of groundwater flow along a valley floor can have marked effects on groundwater. In some cases, new channels can capture all shallow groundwater flow (table 5.3a.3). Capture of shallow groundwater flow is most pronounced where orientation of the stream channel is perpendicular to the direction of groundwater flow (fig. 5.6). This aspect of hydrologic sensitivity is seen in Indian Valley, where a network of headcut trenches, driven by groundwater sapping, migrated into a previously wet meadow complex with no channels. As shown in fig. 5.6d, wet to mesic plant communities persist across much of the valley floor where a new channel trench developed on the downgradient side of the valley with respect to groundwater flow (see the yellow arrow). This is in contrast to another segment of the valley floor that is now void of wet-mesic plant communities, where headcut migration on the upgradient side of the valley

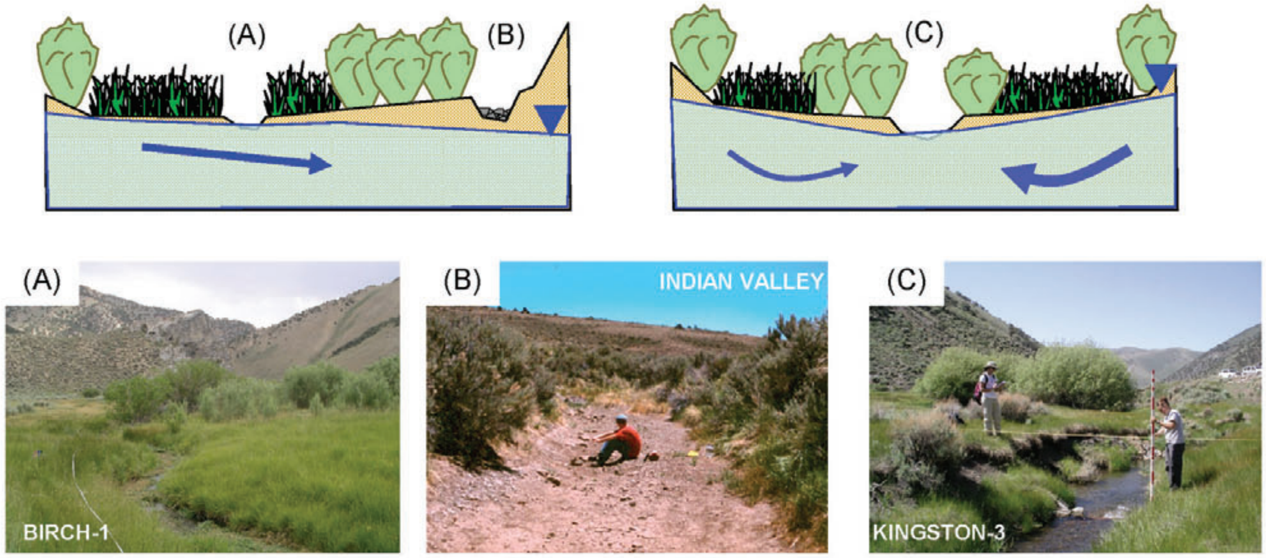

Figure 5.4. Diagrams at top depict three broad types of connections between stream channels and groundwater. These diagrams are generalized to show general topography, groundwater table and flow, wet vegetation, and dry vegetation. The photographs below show the same channel types, indicated by the corresponding letter, in the study meadows. The left diagram (a) shows a spring-fed channel and (b) shows an intermittent runoff channel. Though the spring channel intersects the groundwater table, it does not significantly alter the groundwater table. The runoff channel (b) does not cause lowering of the groundwater table. Gaining, perennial meadow streams, as shown in (c), are connected to groundwater and cause flow convergence and a decline in water table.

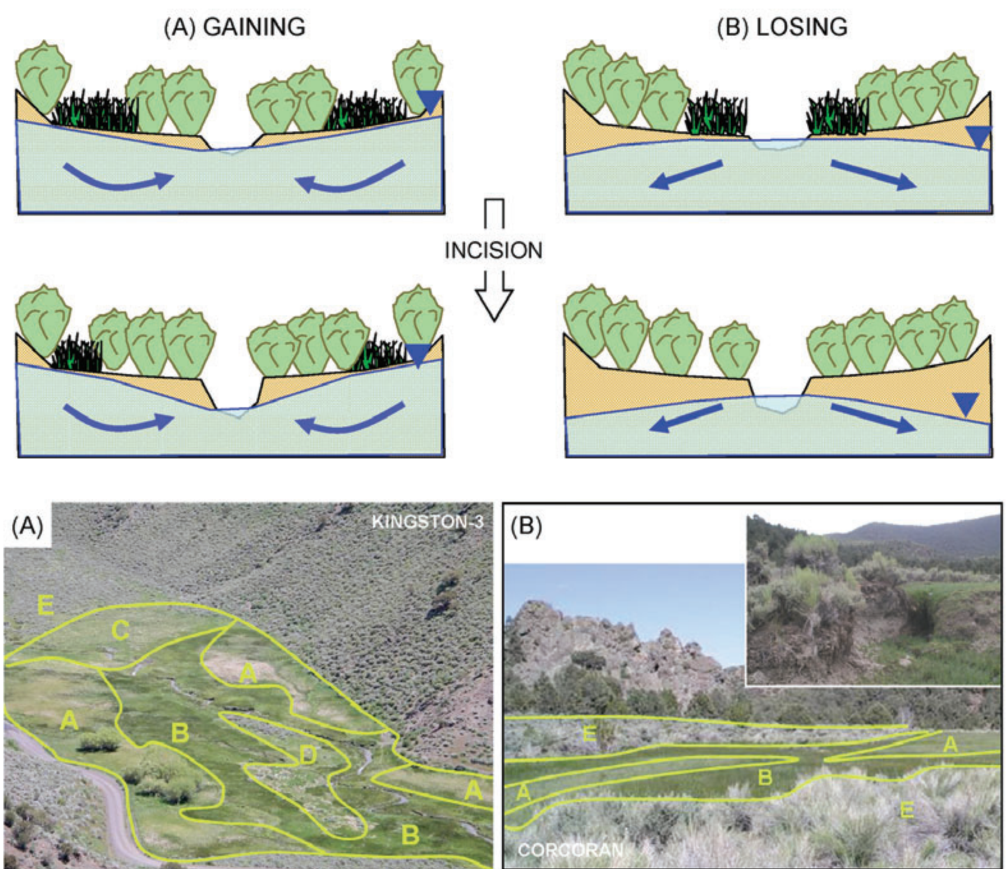

Figure 5.5. Diagrams at the top depict likely response of a gaining stream and a losing stream channel to incision. (a) Incision of a gaining stream, where sustaining water of the meadow complex is not stream water, will result in a limited water table drop adjacent to the channel (a2). (b) Incision of a losing stream, where the stream water supports a meadow complex, may result in loss of wet meadow complex (b2). Plant community patterns in Kingston 3 and Corcoran reflect stream type, as discussed in Chapter 5, with wet to mesic plants at valley margins in a gaining system (a3) and adjacent to the stream in a losing system (b3). Plant community types are A—Wet Meadow (example, Nebraska sedge), B—Mesic Meadow (example, Baltic rush), C—Dry Meadow (example, Nevada Blue Grass), D—Mix: Dry and Sage Meadow, and E—Sage Meadow. Inset photograph (b3) shows a site with sagebrush encroachment into a former wet meadow following incision.

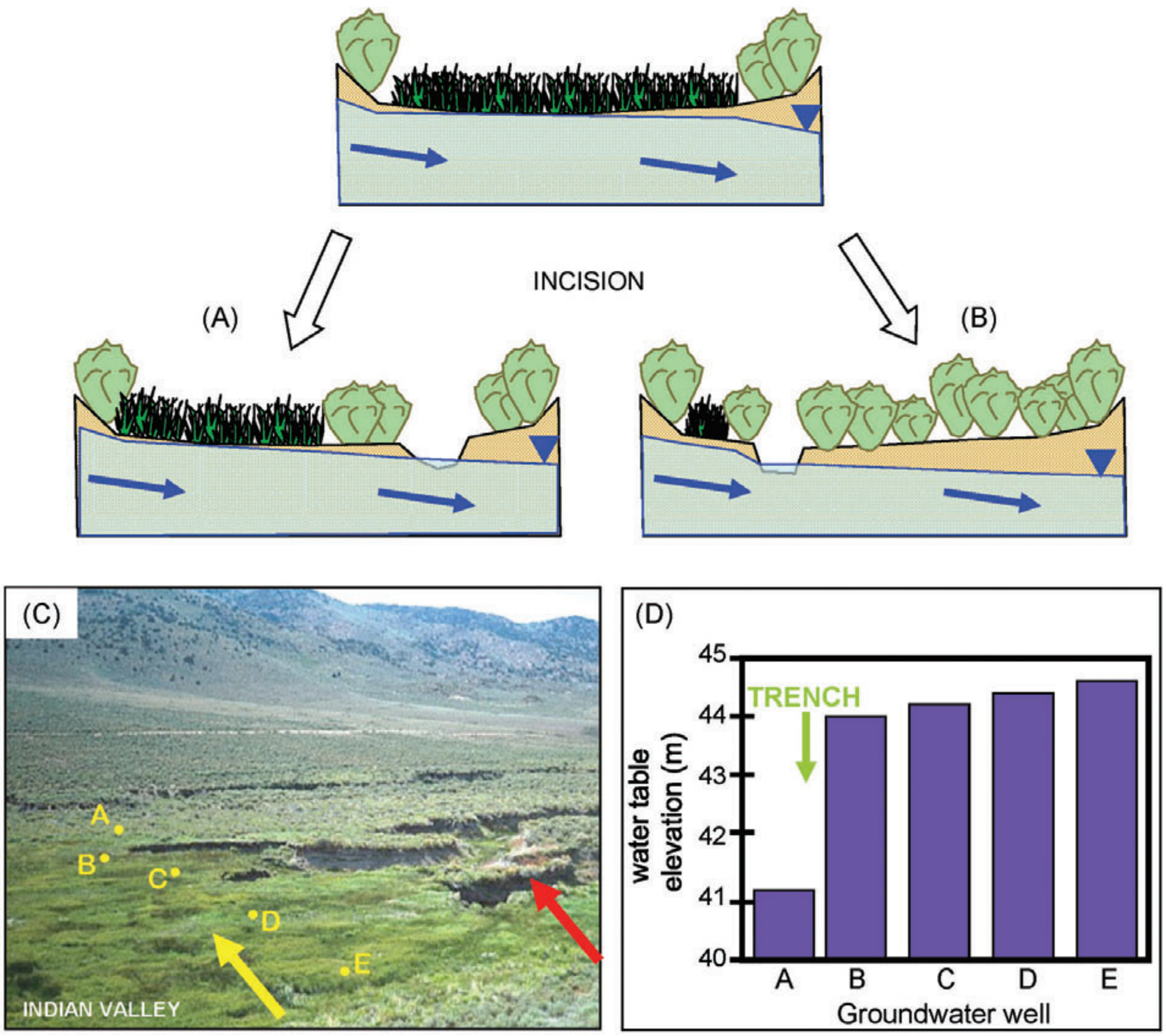

Figure 5.6. (a) New channel incision on unincised valley floor on the down-gradient side of groundwater flow (b) will cause a drop in the groundwater table across only a small portion of valley floor with a minimum loss of wet meadow complex area. In Indian Valley (d—yellow arrow), groundwater wells (A, B, C, D, and E) show cross-valley flow is intercepted by a trench that recently migrated headward due to groundwater sapping, which resulted in a drop of the groundwater table in excess of 2 m (e). Alternatively, (c) channel incision on the upgradient side of the valley floor will cause a water table drop across the remainder of the valley floor within a large loss of wet meadow complex area. The valley floor is all sage meadow in Indian Valley (d) where trenches have intercepted almost all shallow groundwater flow (d—red arrow).

intercepted and lowered the groundwater table across the entire valley floor (see the red arrow). In the meadows of the central Great Basin, it is common for groundwater flow directions to have a strong cross-valley component, especially where side-valley alluvial fans are present (e.g., Kingston 3 meadow). With respect to sensitivity and groundwater, special attention should be given to potential new channels created either by headcut migration or avulsion on the up-gradient side of the valley.

Meadow Stratigraphy

The distinction between meadow hydrologic and stratigraphic controls on sensitivity is somewhat arbitrary because the factors are interdependent. The characteristics of a stratigraphic unit or sequence either support the shallow groundwater system or determine how meadow subsurface hydrology responds to channel incision. Hydraulic conductivity of the sediments surrounding the stream channel (table 5.3b.1) can influence the rate and extent of incision. Incision by a stream that is connected to groundwater (i.e., intersecting the water table) into a coarser-grained, high hydraulic conductivity stratigraphic unit will cause a more extensive drop in the water table than incision into a finer-grained unit (figs. 5.7a and b) (Vidon and Hill 2006). Immediately adjacent to the stream channel, however, the amount of water table drop may be greater in finer-grained material than in coarser-grained material. The principles that underlie this phenomenon are analogous to those used to predict the response of the groundwater table to a pumping well. Aquifer hydraulic conductivity, thickness, and porosity are key factors that control the amount and extent of drawdown

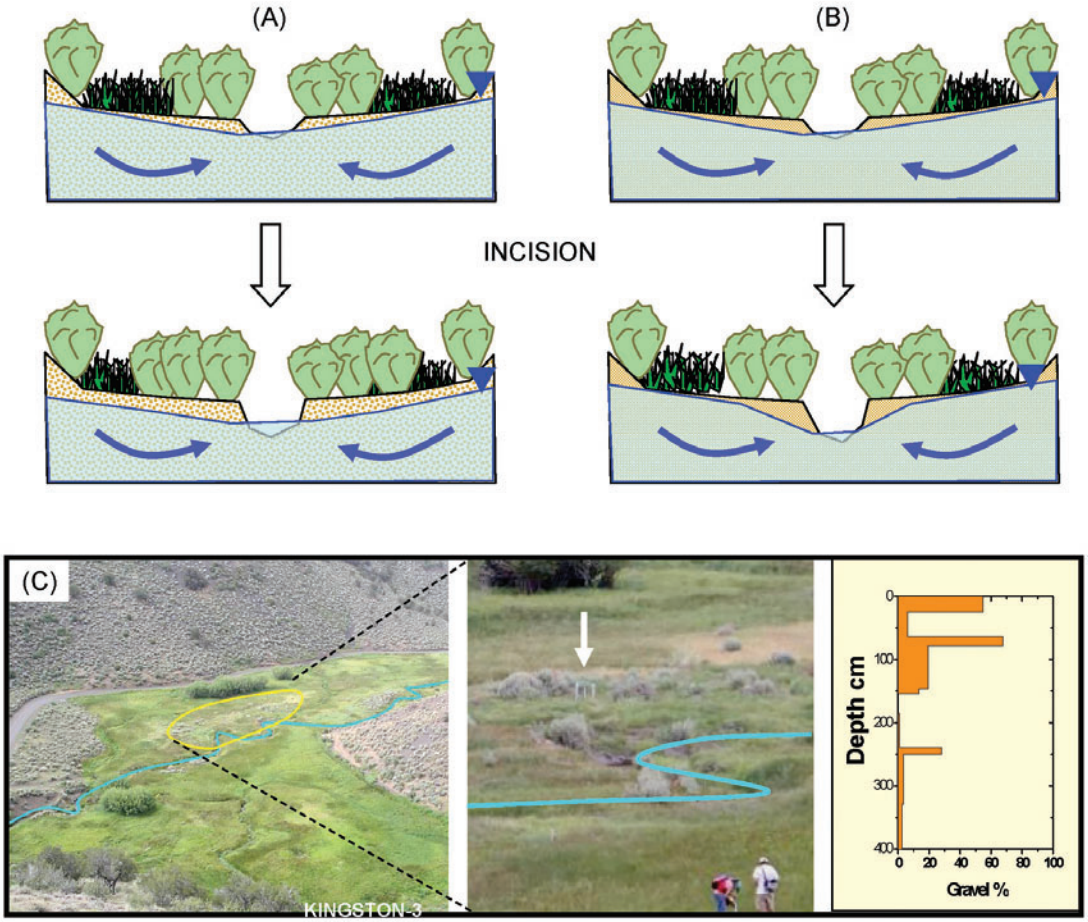

Figure 5.7. Diagrams depict response of meadow to incision of a channel into sediment with (a) high permeability (high hydraulic conductivity) versus (b) low permeability. The drop in the water table will be more widespread in sediments of high hydraulic conductivity. At the Kingston 3 meadow (c), incision of the channel caused a greater drop in the water table on the far side of the creek (see the sagebrush area in the photographs). The sediments at this site are part of an avulsion deposit (fig. 5.1). Analysis of sediment cores (white arrow) showed that two horizons in the upper 1 m contained more than 50 percent gravel.

(Freeze and Cherry 1979). The direct role of hydraulic conductivity on the decline of the water table in response to incision is apparent at the Kingston 3 meadow (Lord and others 2007). Stream incision caused a widespread drop in the water table where it intersected a sandy gravel avulsion deposit (fig. 5.7c), and it caused encroachment of sagebrush. Finer-grained sediments on the opposite side of the stream prevented a wide-spread drop in the water table.

The stratigraphy of most meadow systems is complex, which largely explains why perched water tables, springs, and artesian conditions are so common (Chapter 4). In some cases, the shallow meadow water table is supported by a single hydrostratigraphic unit, typically a low-permeability sedimentary layer that sustains the meadow (table 5.3b.2). In Barley Canyon, a wet and mesic meadow complex was supported by a fine-grained, low-permeability unit overlying a sandy unit of high hydraulic conductivity (fig. 5.8). The stream at this site incised about 2 m wide and breached a confined aquifer that maintained a shallow water table. Once breached, the aquifer drained directly to the stream. The water table drop was so significant that wet and mesic plant communities were replaced by sagebrush and other drier meadow plants. Stream incision or creation of new channels in complex stratigraphic settings is likely to disrupt hydrologic conditions, locally resulting in loss of artesian flow or a perched water table (Shilling and others 2004), both of which would adversely impact the meadow.

Resistance of stratigraphic units is important to stream channel sensitivity and has direct implications to hydrologic sensitivity (table 5.3; fig. 5.9). In streams connected to the groundwater, depth of the channel determines depth of the water table. Where stream incision is inhibited by a resistant layer (such as a gravel-rich layer or a cohesive, fine-grained unit), the layer will prevent further decline in the water table. This controlling factor is demonstrated in many meadows where resistant gravel units that are deposited by side-valley alluvial fans at the downstream end of meadows have prevented or slowed incision (fig. 5.10).

Influence of Gully and Headcut Advancement

Incision results in varying degrees of loss of meadows that are dominated by wet and mesic plant communities regardless of whether incision occurs by individual particle entrainment or by knickpoint processes (Chapter 3). Loss of meadows can be particularly extensive within broad, low-gradient valleys such as in Indian Valley, where headcuts migrate upstream, enhanced by groundwater sapping, and produce a network of deeply entrenched gullies. However, headcut migration can result in water table levels that are located at or just below the floor of the broad, flat-bottomed trench. This occurs because the trench floor serves as the local base-level control for the water table. The net result is that the newly formed trench floor can support wet-meadow

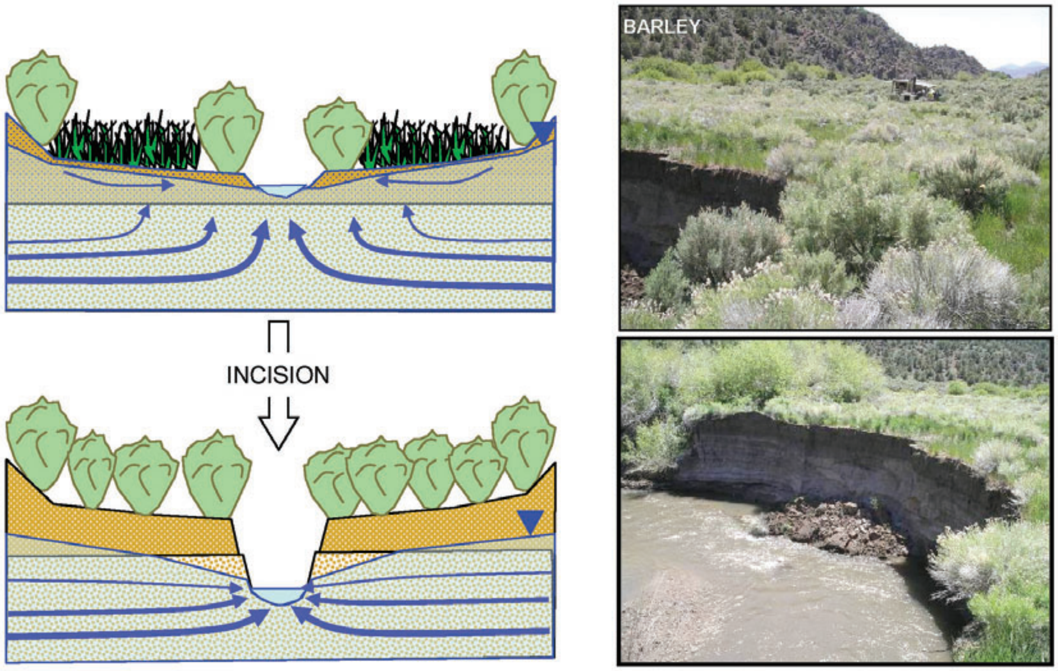

Figure 5.8. Channel incision through a key hydrostratigraphic unit (a and b), such as a low-permeability confining unit, can eliminate the hydrologic framework that supports shallow water tables. In Barley Canyon (c and d), a wet meadow complex was lost when channel incision progressed down through a fine-grained unit into a high-permeability, sandy horizon.

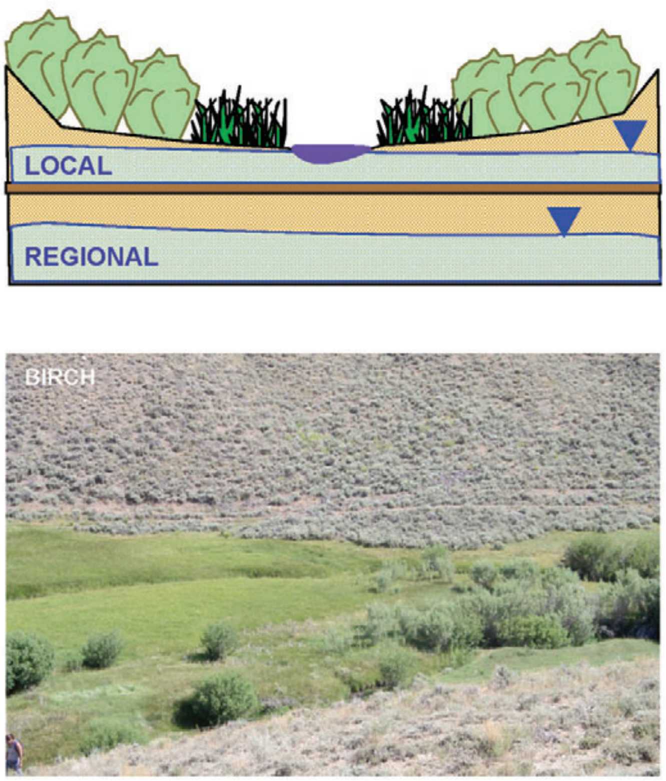

Figure 5.9. Many meadows in the central Great Basin are perched and support perched streams that are underlain by low hydraulic conductivity, confining units. If the water from the perched stream supports the meadow, channel incision through the confining layer would likely result in the loss of wet plant communities, such as is shown in fig. 5.8. The photograph shows the lower portion of the Birch Creek meadow, which is supported by a perched water table.

vegetation (table 5.3c; fig. 5.11) (Jewett and others 2004). In areas where such conditions exist, a new trench-bottomed gully network will offset some of the loss of wet meadow vegetation and the decrease in overall habitat quality.

Influence of Source Waters

The hydrologic sensitivity of meadows is influenced by processes and properties that are external to meadows as well as those within meadows (table 5.3d). Understanding the recharge regions for meadow source waters is critical for effective management of ecological functions controlled by hydrology (Winter and others 2001; Loheide and others 2009). The seasonal patterns of water table levels, or hydroperiods, in meadow complexes are strongly controlled by recharge characteristics. Source waters can be recharged from single or multiple source areas, can vary in scale from local to regional, can occur as diffuse recharge over broad areas or in concentrated areas as stream channel bed-focused recharge, and can occur over short to long periods of time (e.g., Winter and others 2001; Constantz and others 2007; Prudic and others 2007). The annual recharge of subsurface water levels is largely fed by snow, which usually melts over a short period of time, commonly in about one month (figs. 4.18 and 5.12). The response of water table levels in meadows will vary with location of the snowpack, pathway from snowmelt to meadow groundwater, and nature of the connections between surface water and groundwater. In meadows with complex hydrogeology, different parts of the same meadow complex may have different source waters and hydroperiods. These different sources or pathways of water can result in divergent groundwater-level trends within the same meadow—such as what occurs in the Kingston 3 meadow (fig. 5.12).

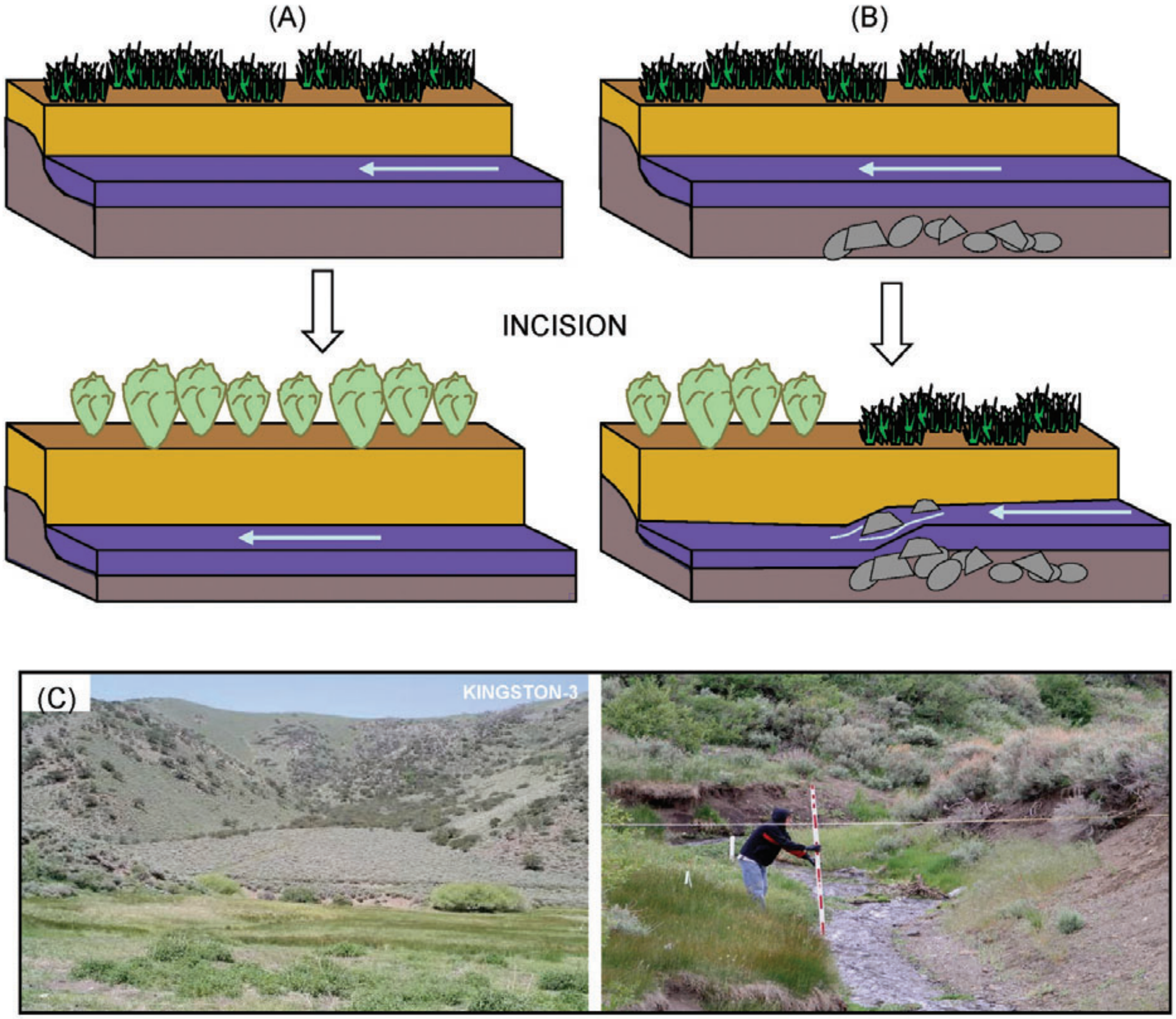

Figure 5.10. Stream incision that is not impeded by resistant stratigraphic units (a) will result in a larger drop in the groundwater table than where a resistant unit is encountered (b) that serves as a local base level control. A cobbly gravel sediment layer deposited by a side-valley alluvial fan at the Kinston 3 meadow serves to stabilize the stream (c) (see fig. 5.1).

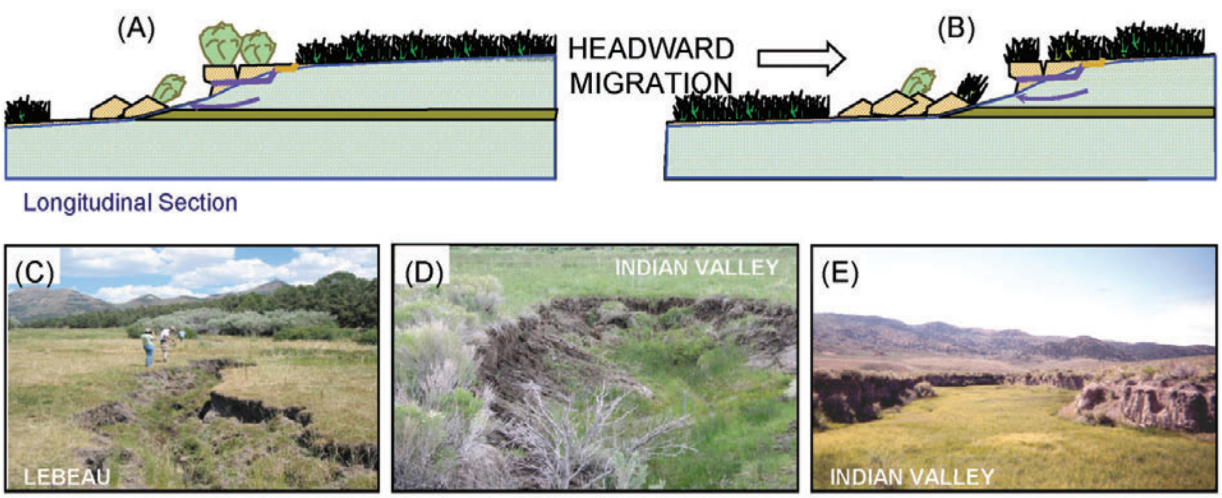

Figure 5.11. Headcut migration of gully-trench systems (a and b) occurs at a continuum of scales in generally fine-grained sediments (c, d, and e) and is driven or enhanced by groundwater sapping. The groundwater table drops to the level of the new trench bottom and may intercept cross-valley shallow groundwater flow (fig. 5.6). With enlargement of the trench system, a wet-mesic meadow complex (e) may develop at the new lower elevation.

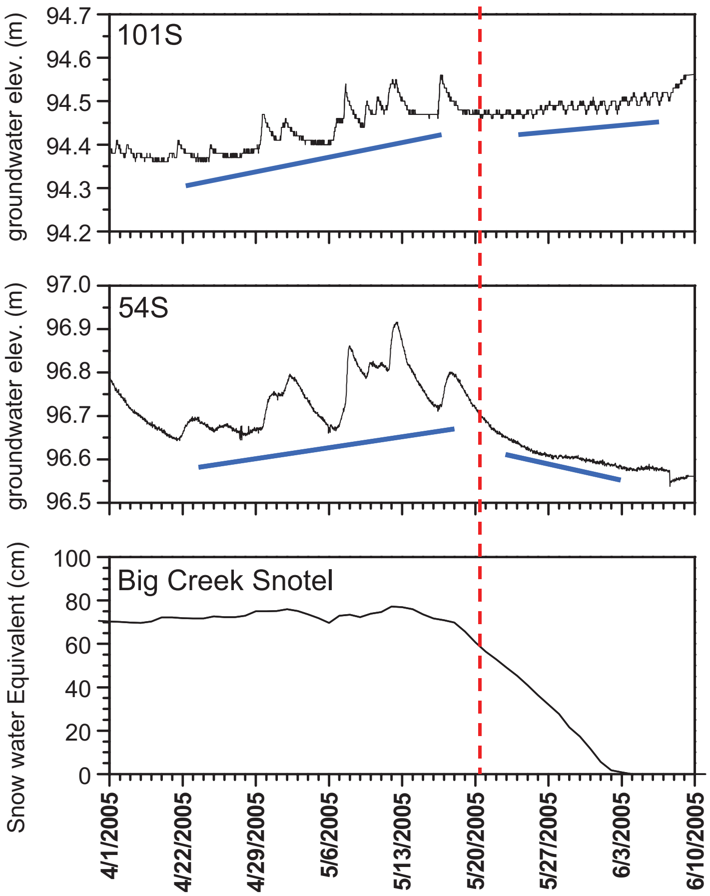

Figure 5.12. Groundwater elevations at two well sites—101S and 54S—in the Kingston 3 meadow show synchronous responses early in the annual, snow-melt driven rise of water levels, but they have divergent responses after May 20th. The lower plot shows snow water equivalent data for the nearby, high-elevation (2650 m) Big Creek SNOTEL site. These divergent responses are explained by stage-dependent differences in connectivity between the source waters and the meadow.

A meadow with a small, source-water recharge area or short recharge period generally will be more sensitive to change than one with a larger recharge area and period. Conversely, meadows with predictable water tables, broad source areas, and long recharge cycles will be less sensitive to natural or anthropogenic change. To understand the hydrologic sensitivity of the system, the source of meadow groundwater needs to be identified and monitored. In lieu of or in addition to monitoring source waters, gathering continuous groundwater and stream water level data should be a management goal to at least understand the timing and patterns of recharge cycles.

Hydrologic Sensitivity Summary

The sensitivity of meadow complexes in the central Great Basin is controlled by numerous physical and biotic factors. The areas that are most naturally sensitive are most likely to change in response to anthropogenic activities. These meadow ecosystems require shallow water tables; therefore, understanding hydrogeologic controls on overall sensitivity is critical. Hydrologic sensitivity is controlled largely by meadow hydrogeology, especially by the interaction of groundwater and stream water, stratigraphy, geomorphic processes, and the area and timing of groundwater recharge. While all of the variations in these controls cannot be readily quantified, there are traits associated with different degrees of sensitivity. High hydrologic sensitivity is indicated by: (1) a meadow stream channel that has a continuous connection between groundwater and stream water, especially if the stream water recharges the groundwater; (2) complex stratigraphy, including highly permeable layers; (3) an active stream with high geomorphic sensitivity; and (4) source waters that recharge groundwater over limited space and over short periods of time. In contrast, low hydrologic sensitivity is indicated by meadows that: (1) are not intersected by stream channels that convey runoff; (2) are supported by regional groundwater discharge; (3) have simple stratigraphic sequences; and (4) have source waters of wide areal extent that recharge over extended periods of time.

The task of assessing sensitivity of meadow complexes can be difficult, but much can be learned by first identifying the processes and properties that control hydrologic and geomorphic sensitivity by assessing characteristics described in this chapter (tables 5.1 and 5.3). A preliminary grouping of meadows by sensitivity traits is an important first step in management of meadow systems, even though it must be followed by more detailed studies of target meadows. The discussions in Chapter 9 on meadow management and treatment options broaden this discussion by describing how sensitivity can be used as part of a strategy for resource scientists to monitor, manage, and restore meadow complexes.

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