Chapter 3: Geomorphic Processes Affecting Meadow Ecosystems

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Introduction

Three geomorphic processes are of primary concern with respect to the current and future state of wet meadow ecosystems: channel incision, avulsion (the abrupt movement of the channel to a new location on the valley floor), and gully formation. Gully formation often is accompanied by upvalley headcut migration and a phenomenon referred to as "groundwater sapping" that is defined as erosion of bank materials by groundwater flow. In this chapter, we examine the effects of each of these processes on meadow complexes. Although these processes are discussed separately, they are often interconnected and the rates at which they proceed depend on their interactions. Therefore, the potential to stabilize or rehabilitate a specific meadow must not only include an evaluation of the individual processes but also their combined effects.

Channel and Valley Incision

Our interest in channel incision stems largely from the potential of a lowered streambed to result in a drop of the adjacent water table and a subsequent change in riparian meadow vegetation and aquatic habitat. Incision also may lead to other detrimental geomorphic effects, including: (1) an increase in bank heights, which can decrease the frequency and magnitude of overbank flooding and increase rates of bank erosion; (2) a change in cross-sectional channel morphology; and (3) a loss in complexity of the streambed and an overall decline in aquatic habitat. In general, incision occurs anywhere that sediment removed from the reach exceeds the amount entering the reach, provided that the stream's power is capable of moving the bed material (substrate). Both sediment supply and stream power vary through time and space. Thus, the magnitude and rate of incision vary along the channel at any given time, and through time at any given location. In addition, the means through which the bed is actually lowered can involve several different processes, depending on the nature of the bed and bank materials, the stream's capacity to transport sediment, and the pre-existing channel morphology. The most important of these processes are erosion of the channel bed through entrainment of individual particles and the formation and subsequent migration of knickpoints.

Channel Incision by Particle Entrainment

Where an integrated stream network exists, the most ubiquitous process through which channels in the upland basins incise is through the grain-by-grain entrainment of sediment from the channel bed and its subsequent downstream transport at a rate that exceeds its replenishment. This grain-by-grain transport process can occur anywhere that unconsolidated sediment forms the channel floor but, in these study sites, it is most prevalent along stream segments that are located between meadow complexes. The tendency for incision to occur is driven largely by the region's history of intense hillslope stripping of fine sediment between approximately 2580 and 1980 years BP, a process that has reduced sediment input to the axial drainage systems. Specifically, the inability of material to be transported off of hillslopes and into the drainage network has resulted in a general lack of bedload and has contributed to the tendency for channels to incise.

Given that bedload transport rates are likely to increase with increasing discharge, most incision occurs during periods of relatively high runoff. For example, repeated measurements of cross-sectional channel geometry along eight incising reaches in five watersheds (Big Creek, Kingston, San Juan, Cottonwood, and Washington; fig. 1.7) showed that while bed degradation during the low runoff years of the early 1990s was limited, incision during the relatively high runoff period of 1995 was significant and ranged from 5 to 36 cm (fig. 3.1a; Chambers and others 1998). Incision was accompanied by significant bank undercutting (up to 18 cm; fig. 3.1c) as well as by bank loss and/or deposition (-6 to +38 cm; fig. 3.1b). Deposition along the banks was primarily associated with growth of pre-existing gravel bars. Variations in the degree of channel incision and bank modification were related to size of the bed material, cover of bank vegetation, and age and stem density of willows growing on terrace surfaces along the channel margins.

The correlation between rapid rates of incision with years of relatively high runoff also is supported by dendrogeomorphic data. Terraces located along the eight surveyed reaches described above were dated by determining the maximum age of willows that colonized their surface (fig. 3.2) using dendrochronological methods (after Sigafoos 1964; Phipps 1985). The presumption is that extensive willow colonization occurred shortly after the geomorphic surface was formed, and the sediments were no longer being transported during low to moderate runoff events (Sigafoos 1964). The results show that willow age correlates with height of gravel terraces located along the channel. Maximum willow ages

Figure 3.1. (a) Amount of stream incision, (b) bank erosion, and (c) bank undercutting measured at monitoring cross sections during the high runoff year of 1995; SJ = San Juan Creek; BC = Big Creek; WC = Washington Creek; KC = Kingston Creek; and CW = Cottonwood Creek.

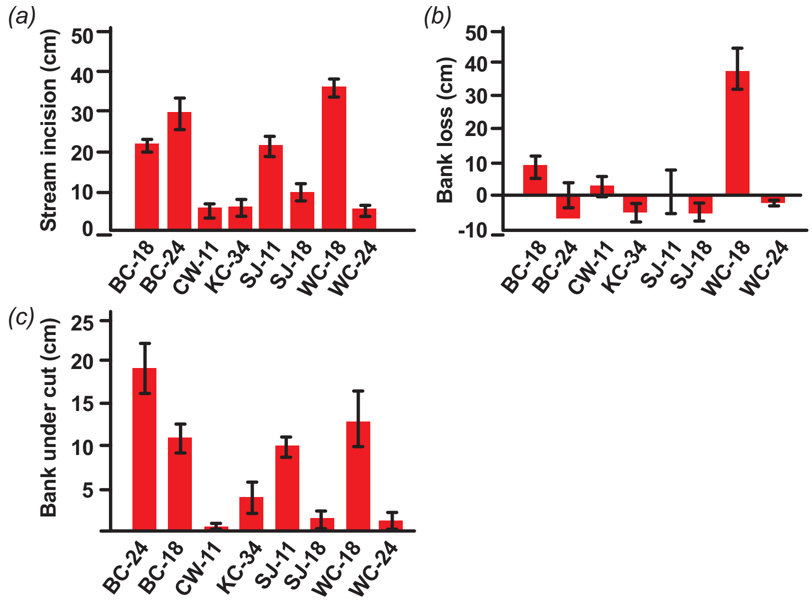


Figure 3.2. Willow covered terrace surface located along Big Creek. Colonization of the surface is assumed to occur following incision and the cessation of annual particle entrainment.

for the most recent terrace at the time of data collection (in 1997) were 11 to 12 years, corresponding to high runoff events in 1983-1984. The maximum ages of other willows clustered around 18 to 20 and 24 years, as measured in 1997. These willows presumably colonized new terrace surfaces created by channel incision during high flows and overbank flooding in the 1970s (1973, 1975, and 1978; fig. 3.3). Older stands of willows could not be accurately dated because individual willow stems survive less than 50 years (Chambers and others 1998). However, older stands were found on terraces above the geomorphic surfaces that were created in the 1970s. Thus, the stands were likely to have established either before the recent episodes of channel incision or along a limited number of stream reaches that had not incised.

Most watersheds within the study area exhibit convexities in the longitudinal profile of the axial channel, which represent zones of inherent instability that are prone to entrenchment. Once incised, base level is lowered and upstream reaches must adjust. Importantly, spatial variations in the rate and magnitude of incision are closely related to the degree to which erosion has lowered local base level along concaved upstream reaches, most of which are produced by side-valley alluvial fans. Where incision occurs, a proportional amount of upstream incision is likely to follow, either by means of individual particle transport or through knickpoint processes.

Incision by Knickpoint Processes

While channel incision by means of particle entrainment and transport is wide-spread, much of the observed incision is associated with the localized development and migration of knickpoints. Knickpoints, broadly defined as abrupt changes in channel gradient, are generally associated with episodes of entrenchment in response to a lowering of base level. Detailed mapping of knickpoint distribution along the

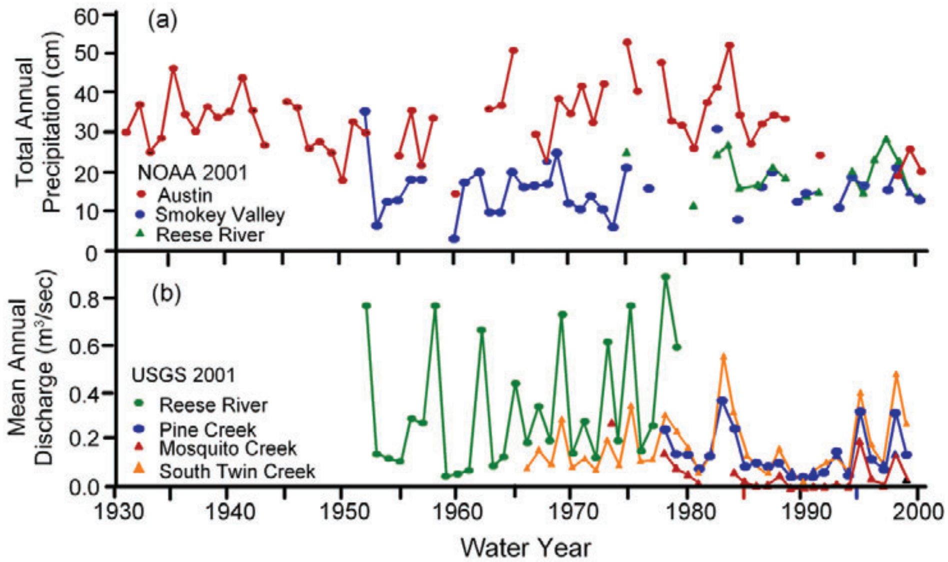


Figure 3.3. (a) Total annual precipitation measured for Smokey Valley, Reese River, and Austin, Nevada; (b) mean annual discharge for selected stream systems in central Nevada.

downstream reaches of 10 basins, combined with field observations from more than 20 additional watersheds in central Nevada, demonstrate that knickpoints can be found throughout the drainage network, with the exception of zero- and first-order streams (Germanoski and Miller 2004). However, knickpoints are concentrated at or immediately upstream of convexities in the valley floor. Knickpoints are particularly prevalent at and upstream of side-valley alluvial fans that influence valley/channel gradients (fig. 3.4). Where these fans occur with meadow complexes, knickpoints play a critical role in channel incision through the meadows.

Experimental and field studies conducted over the past three decades have shown that the nature of knickpoint migration and evolution can be highly variable from site to site (fig. 3.5) and is dependent on the composition of the bed material, variations in the material's resistance to erosion (particularly the presence of stratification), and the relationship between channel bed shear stress and the critical tractive force required to initiate particle motion (Gilbert 1896; Pickup 1975; Gardner 1983; Cosby and Whipple 2007). Knickpoints found at the toe of side-valley alluvial fans are composed primarily of cobble or boulder-sized clasts, which are significantly larger than bed material located either up- or downstream of the knickpoint face. The height of the knickpoint face is equivalent to the diameter of the clasts that form the knickpoint. Thus, the knickpoint represents the cross-channel alignment of several large, interlocking boulders that require relatively

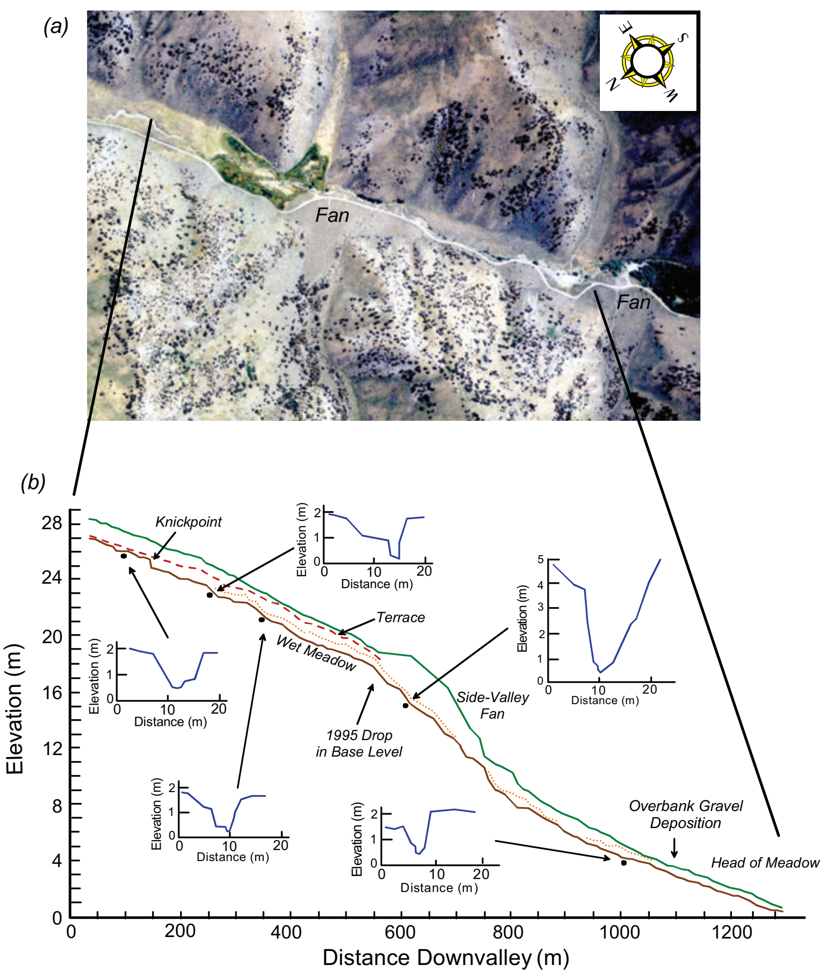


Figure 3.4. Longitudinal profile showing changes in channel gradients across a large side-valley alluvial fan in Kingston Canyon. Note the drop in elevation of the valley floor across the fan, a feature that creates a local zone of channel instability. Incision through the fan is limited by course fan sediments within the channel bed.

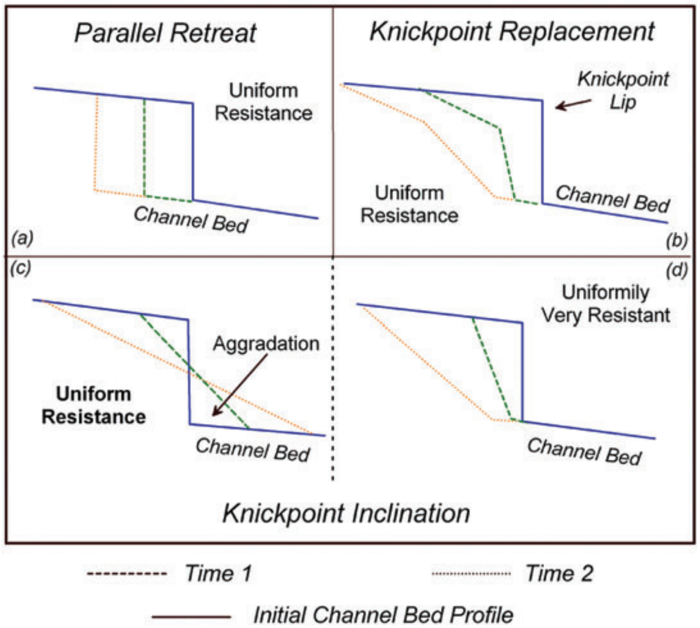


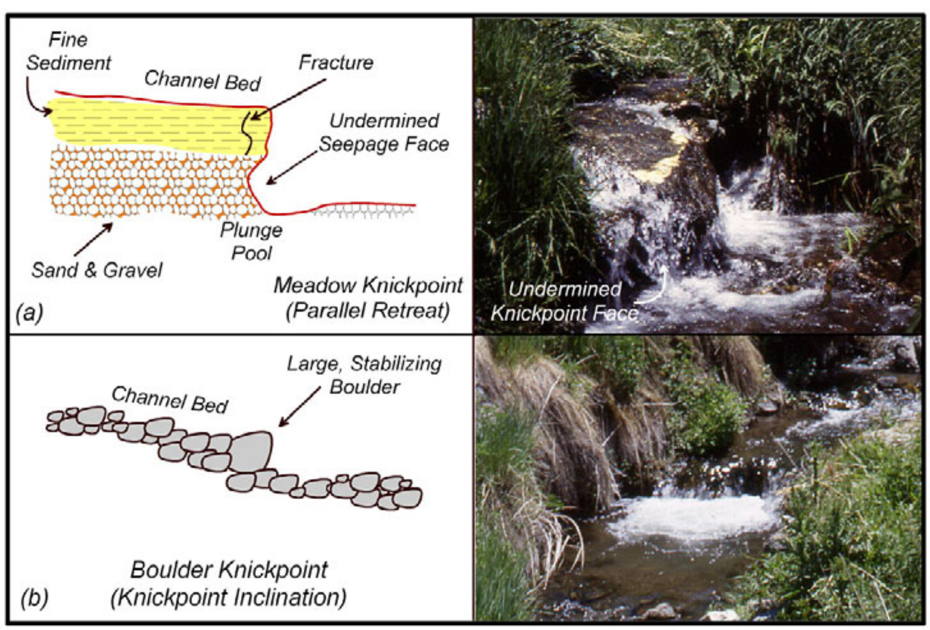
Figure 3.5. Three models of knickpoint evolution described by Gardner (1983). Knickpoints in central Nevada primarily evolve by (a) parallel retreat when formed in fine-grained sediment, and by (c) knickpoint inclination when developed in non-cohesive, coarse-grained sediment. In the latter case, knickpoint advancement is limited, but the process of knickpoint inclination results in a lowering of local base level, which is subsequently translated upstream.

high values of shear stress to be moved (figs. 3.6a and b). It is not entirely clear if the boulder-sized material that forms the knickpoints is transported into place, or if knickpoints represent more resistant zones in the channel bed that are exposed as finer materials are entrained and transported out of the reach. It is likely that both mechanisms occur depending on the local bed material composition and flow conditions. What is significant about these knickpoints is that once one or more of the lip-forming boulders are moved downstream, finer material immediately upstream of the knickpoint face can be transported through the breach. This allows the slope of the channel bed upstream of the knickpoint to decline. In most cases, the finer material is not redeposited immediately downstream of the knickpoint but is transported out of the area, resulting in a drop in base level and the evolution of knickpoint morphology by means of knickpoint inclination (fig. 3.5c). The erosional resistance of these knickpoints is important because it largely dictates the rate at which the channel bed, composed predominantly of fan sediment, can be incised.

Knickpoints along stream reaches that traverse meadows and that are located upstream of the side-valley fans (fig. 3.6a) are different from those found within the non-cohesive gravels of the over-steepened fan reach. Here, the knickpoints are formed in fine-grained cohesive sediments that typically underlie a thin veneer of gravel in the channel bed of the meadow complex. These types of knickpoints usually migrate upstream through the meadow complex for considerable distances and eventually disappear where the composition of the channel bed becomes dominated by gravel rather than fine-grained alluvium (i.e., silts, clays, and fine sand). During upstream migration of the knickpoint, an inset terrace is commonly formed that extends upstream from the side-valley fan through the meadow complex and beyond (e.g., fig. 3.4b, dashed line). The occurrence of the terrace upstream of the meadow (and the known upstream extent of knickpoint migration) suggests that the effects of the base-level drop at the fan are realized over a significant portion of the axial drainage.

The style of knickpoint migration and evolution that is observed within the meadows is referred to as parallel retreat (fig. 3.5a) because the knickpoint face remains roughly vertical as it migrates upstream (fig. 3.6a). Gardner (1983) argues that three factors are needed for parallel knickpoint retreat:

Figure 3.6. Morphology of knickpoints commonly observed along incised channels. (a) Knickpoint developed in fine-grained sediment; (b) knickpoint developed in coarse-grained sediment. Knickpoints formed in fine-grained, cohesive sediments migrate upstream by means of parallel retreat, whereas upstream advancement of knickpoints formed in coarse sediment is limited. Both photographs were taken along Kingston Canyon in 1997.



(1) an erosionally resistant layer that forms the knickpoint lip, (2) an underlying unit with lower resistance to erosion, and (3) the ability of stream flow to remove sediment from the base of the knickpoint. The removal of sediment from the base of the knickpoint can create a plunge pool by undercutting the resistant cap layer. The knickpoint then migrates upstream (retreats) as the material that forms the knickpoint face fails. Knickpoint retreat is commonly observed where streams are developed in alluvial materials characterized by varying resistances to erosion (Holland and Pickup 1976; Patton and Schumm 1981; Gardner 1983; Miller and others 1990), as is the case for most meadow complexes in the study area.

Most meadow systems are characterized by deposition of fine-grained silts and clays over the valley floor and the periodic deposition of sand and gravel both within the channel and as localized, lobate overbank deposits. The latter deposits tend to be associated with rare episodes of sediment influx to the drainage network during storm events. These diverse depositional sequences result in a layered stratigraphy that is prone to incision by knickpoint retreat. Erosionally resistant materials required for knickpoint retreat also appear to be related to soil development in both fine- and coarse-grained alluvium during periods of relative stability. Of particular importance are soils developed in the surface of Neoglacial (Qa1, fig. 2.1) deposits that possess significant quantities of clay and are particularly resistant to erosion. Another important property of these soils (and other units with relatively large amounts of silt and clay) is that the fine sediment limits vertical groundwater flow. As a result, where these fine-grained units are present, horizontal flows are enhanced, creating zones of groundwater seepage along the channel banks immediately above the less permeable layer. Bank seepage in these areas can be so significant that it results in erosion of less resistant (cohesive) bank materials, bank undercutting, and subsequent bank collapse. Although less obvious, groundwater flow also may lead to erosion and undercutting of materials beneath the knickpoint lip, particularly in areas that are characterized by upward flow gradients and/or artesian conditions (fig. 3.6a). Thus, knickpoint retreat appears to be aided by groundwater sapping processes, which tend to be spatially limited to meadow environments.

The mechanisms of channel incision correlate closely with the size and composition of material in the channel bed. Knickpoints along streams that traverse side-valley fans are composed of boulders and evolve by knickpoint inclination (fig. 3.6b). Knickpoints within meadows are composed of cohesive, fine-grained sediments and migrate upstream by means of knickpoint retreat. Upstream of meadows, knickpoints are generally lacking, and channel incision occurs by entrainment of individual clasts. Given that the current distribution of the geologic materials that form the channel bed is related to depositional processes that occurred in the past, it follows that the system's geological history has played a significant role in dictating the nature of modern channel processes.

An important observation from a management perspective is that once a drop in base level at the fan has taken place, further degradation is likely to occur somewhat rapidly. For example, aerial photographs suggest that the axial channel in Kingston 3 meadow (fig. 3.4) had been stable since at least 1965. Once base level had been lowered by a flood in 1995, the entire meadow system exhibited channel incision within a relatively short period of time (five years).

In many cases, wet meadows are characterized by an axial channel fed by upstream runoff, and one or more smaller tributaries fed predominantly by spring flow. During knickpoint migration, not all parts of the drainage network within these meadows are affected equally. For example, as the knickpoint migrated through Kingston 3 meadow, the base level drop along the axial stream created additional knickpoints within the spring-feed tributary channels. These knickpoints have not migrated more than a few meters upstream of the tributary's confluence with the axial channel, presumably because stream power dropped significantly (see Cosby and Whipple 2007). However, these knickpoints represent points of instability that can lead to rapid channel and valley incision under certain conditions.

Gully Formation Along Steep Valleys

As previously discussed, well-defined channel networks are incised by either knickpoint processes or entrainment of individual particles. In contrast, unincised meadows or meadows that possess shallow, discontinuous channels are usually entrenched by a different set of processes involving gully formation and headcut migration, both of which are promoted by groundwater sapping (sometimes called seepage erosion). The nature and rate at which these processes occur differ between basins, but basins can generally be grouped into two types: (1) those characterized by relatively steep valley floors that are underlain by highly permeable sediments; and (2) those that exhibit low-gradient valleys, relatively large meadows, and a mixture of sediment sizes within the valley fill. In this section, we discuss the formation of gullies and the resulting transport and deposition of sediment within basins that possess relatively steep and narrow valley floors.

Of particular concern is the potential for extremely rapid development of relative large gullies. This is prevalent within basins that are underlain by quartz monzonites and granodiorites of middle Jurassic age that weather into coarse sand and granule-sized sediment (called grus). Grus is particularly susceptible to erosion by groundwater because it is non-cohesive and highly permeable, allowing for rapid rates of groundwater flow. As a result, valley incision often involves a positive feedback mechanism in which the onset of incision and the formation of a distinct channel produce groundwater flow convergence, higher effective pore pressures, and enhanced seepage erosion and undercutting. As the channel grows, these processes are enhanced to the point that upstream headcut migration can occur with little or no overland flow, provided that the failed bank material is carried away from the base of the slope by groundwater discharge into the channel.

Perhaps the best example of this process (or sequence of processes) is provided by Marshall Canyon, a 4.9-km^2 basin located approximately 2 km south of Austin on the western flank of the Toiyabe Range. In May 1998, the valley floor in the upper section of the basin was rapidly incised over a period of a few days in response to heavy rainfall and melting of a relatively large winter snowpack (fig. 3.7a, b, and d). Germanoski and others (2001) found that erosion, deposition, and transport of sediment during and following the event occurred in distinct zones, called "process zones," along the valley bottom. These process zones were mapped on aerial photographs in June 1998 immediately following valley incision (fig. 3.8). The most significant zone of valley entrenchment (Erosion Zone 1; fig. 3.8) was located at the head of the drainage system in an area characterized by several side-valley springs and the convergence of low-order tributaries draining headwater reaches (fig. 3.8). The zone was characterized by an unincised valley floor prior to the event. However, erosion created a flat-floored trench with nearly vertical walls. The trench was about 7 to 10 m wide, up to 6 m deep, and terminated upstream in three amphitheater-shaped, vertical headcuts that were separated by narrow "islands" of valley fill (fig. 3.7a). There was no evidence immediately after the event to suggest that the three headcuts were eroded by overland flow. Rather, it appeared that headcut development and migration primarily resulted from a combination of seepage erosion (sapping) and slope failure by mass wasting processes. Although headcut development and migration were not observed, the following factors were likely to have occurred in the process:

- Localized incision of the valley fill along a low-relief depression, creating a shallow, discontinuous gully system;

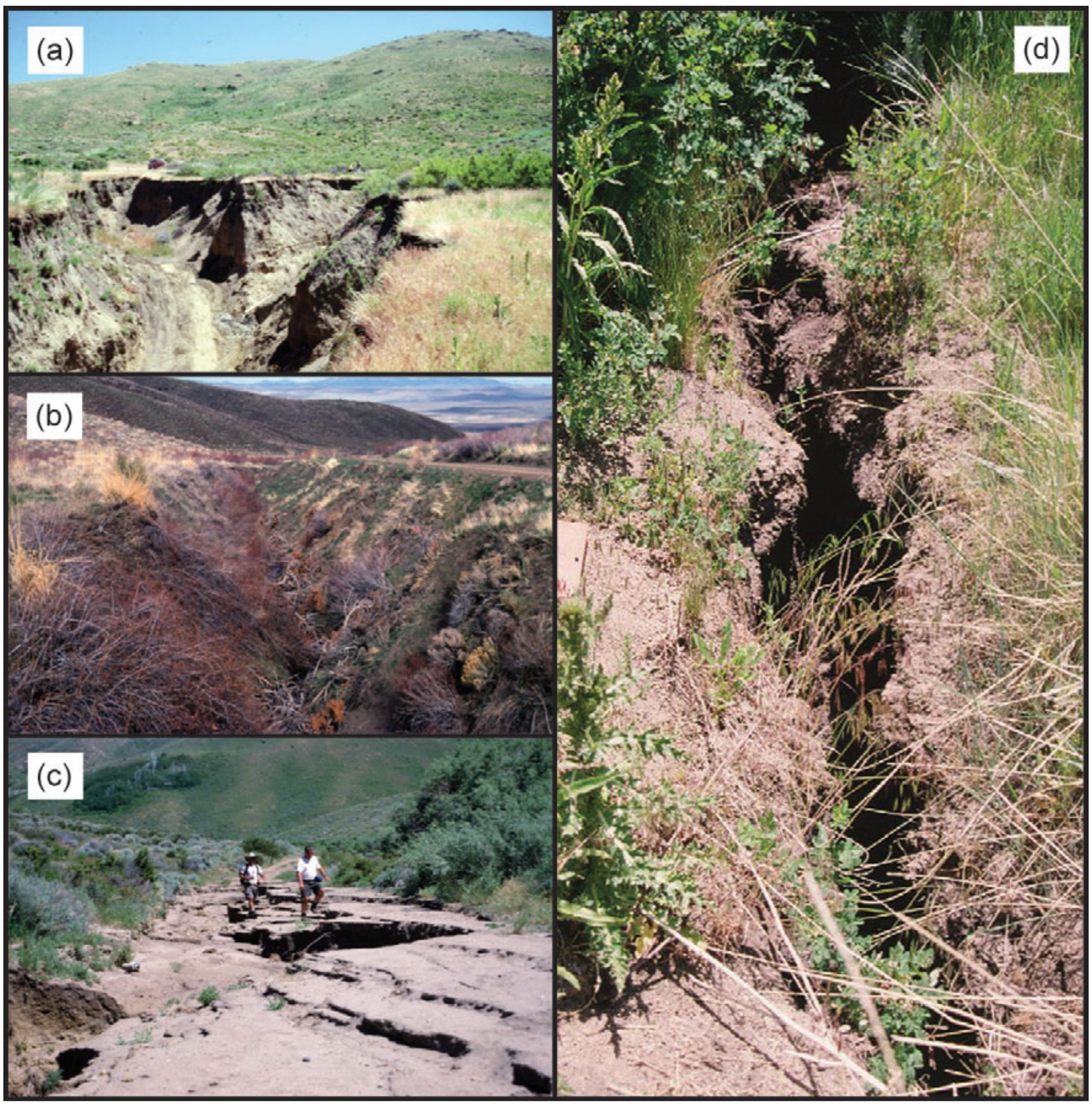


Figure 3.7. Major types of process zones recognized along the valley of Marshall Canyon: (a) Erosional Zone 1; (b) Transport Zone 1; (c) Depositional Zone 1; and (d) Incised channel within Erosion Zone 2. See fig. 3.8a for process zone locations.

- Convergence of both surface and, more importantly, groundwater flow as the depth of incision increased; and
- A shift in process mechanics away from incision by means of individual particle entrainment to incision by means of seepage erosion (sapping) and subsequent slope failure. The sapping process probably involved erosion of particles from the base of the trench, thereby undermining the headcut face and destabilizing the slope.

Downstream of Erosion Zone 1, sediment removed from the trench was transported through a V-shaped channel that was produced by incision during the high runoff years of 1983 and 1984 following partial burning of the basin by a wildfire in 1981. This V-shaped transport zone (Transport Zone 1) extended down-valley for approximately 100 m before terminating in a lobate-shaped deposit labeled “Depositional Zone 1” (figs. 3.7c and 3.8). The lobate deposit began as an inset channel fill that spilled onto the valley floor, covering a down-valley distance of approximately 60 m. Not all of the sediment that was cut from the trench in Erosion Zone 1 was deposited on the lobe within Depositional Zone 1. In fact, the majority of sediment produced by the event passed through the reach where it was routed into and out of Transport Zone 2 before coming to rest as a very large depositional lobe similar to that found upstream. The primary difference was that the second deposit was much larger than that found upvalley; it was almost 400 m long and had a maximum width of 75 m. Stratigraphic data show that a channel was present throughout this reach (Depositional Zone 2) prior to the 1998 event. The channel was completely filled to a depth of as much as 1.5 m during the event before deposition spilled onto the valley floor, creating overbank deposits with a maximum thickness of 0.4 m. Both the overbank lobate deposits and the channel fill were re-incised to depths ranging from 0.5 to 1.5 m immediately after sedimentation ceased.

Downstream of Depositional Zone 2, the valley floor is incised by two narrow (0.25 m wide) and deep (1.9 m) channels that terminate upstream in vertical headcuts (fig. 3.7d). Incision along this reach of the valley floor (Erosion Zone 2) appears to have started well before 1998 and is ongoing, although rather slowly. Farther downstream of the convergence, the two channels coalesce and the channel widens to a “bankfull” width of 4 m. Ultimately, the channel grades downstream onto the valley floor within Depositional Zone 3.

Field surveys and cartographic data show that the patterns of erosion, transport, and deposition are largely controlled by valley morphology. Erosion during the 1998 event occurred in areas where valley gradients and, therefore, shear stress were greatest (fig. 3.8). The transport zones created by flows in 1983 and 1984 also represent reaches of relatively high gradients in comparison to the depositional zones. These reaches did not incise in 1998, presumably because they had already been entrenched, and the V-shaped channels that were created were efficient at routing sediment downstream. In contrast to zones of erosion and transport, deposition occurred where channel gradients decreased and

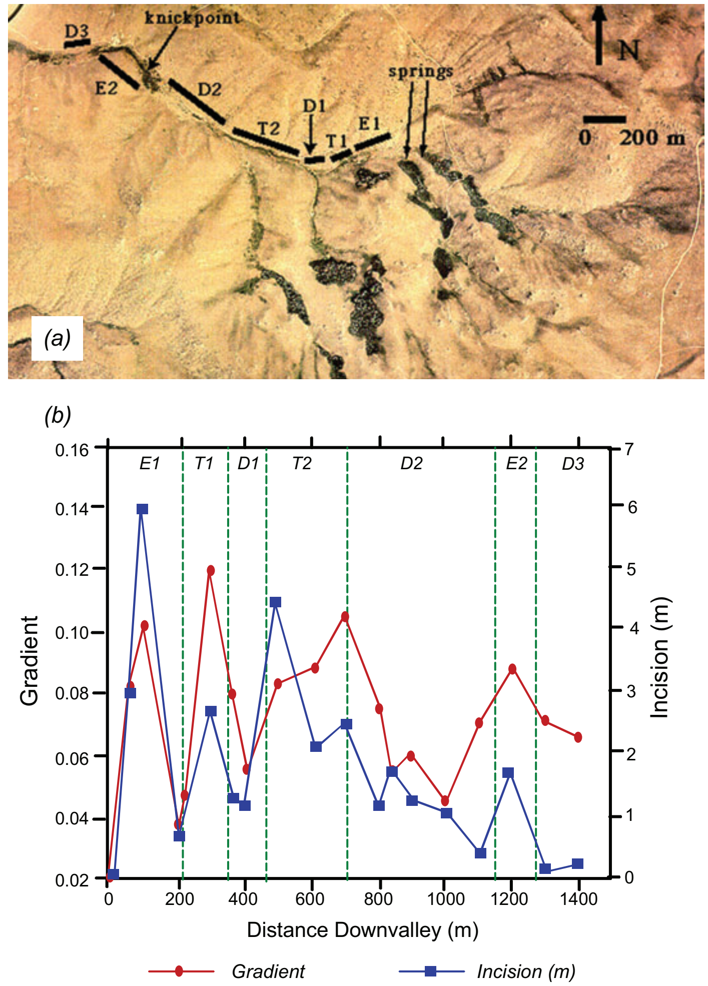


Figure 3.8. (a) Distribution of recognized process zones along the valley of Marshall Canyon in 1998; (b) changes in gradient and depth of incision along Marshall Canyon in 1998 as a function of process zone type. Gradient and depth of incision are relatively low in depositional zones compared to erosional zones.

valley floor widths increased (fig. 3.8). Thus, the observed pattern of erosion and incision following the 1998 event reflected a combination of channel gradients, valley width, the availability and nature of groundwater flow, and the system’s geomorphic history.

The pattern of gully erosion and deposition that was observed in Marshall Canyon is common in other basins in the area, although the rate of gully development is much slower. In Corcoran Canyon (fig. 1.7), for example, incised channels are repeatedly associated with narrow, generally steeper reaches of the valley floor (fig. 3.9). In contrast, unincised reaches of the valley floor are associated with wider, lower-gradient valley segments. Importantly, most meadows are found within these wider, lower-gradient environments (figs. 3.9 and 3.10). While the meadows are associated with valley reaches that promote deposition, they may be affected by upstream migration of headcuts, which initially develop downstream along narrower, steeper transport zones where surface flows are concentrated and tractive forces are higher. In addition, incision appears to be enhanced by emergence

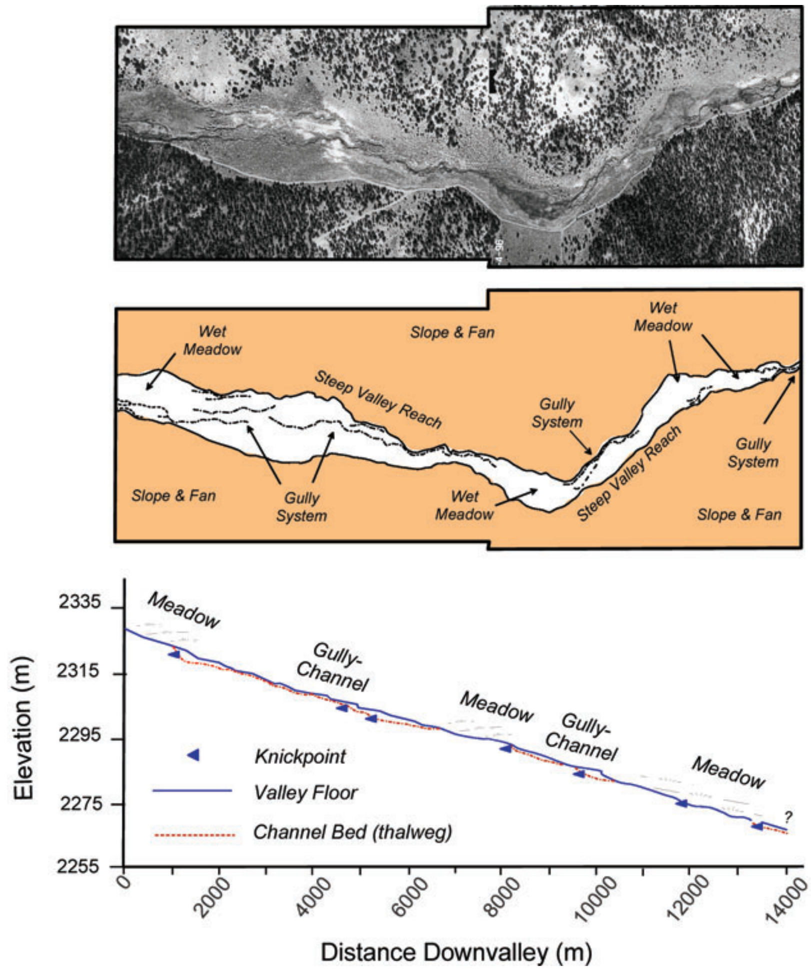


Figure 3.9. Spatial variations in valley width and gradients along Corcoran Canyon. Channel incision commonly begins along narrow, steep reaches with high erosive flows and migrates upstream where it may negatively impact the meadow complex.

of groundwaters under artesian conditions via springs that increase surface runoff at the downstream portion of the meadows. For instance, in Corcoran Canyon, multiple headcuts are found along the downstream segments of the meadows where groundwater springs provide additional water to the surface. In summary, entrenchment is promoted by a combination of factors, including narrow valleys that concentrate surface flows, steeper valleys that increase the flow's ability to entrain particles, and groundwater discharge that increases the magnitude and frequency of surface runoff. Reaches of a valley floor that are characterized by one or more of these properties are particularly sensitive to incision by gully formation and advancement.

Gully Formation, Headcut Migration, and Depositional Processes Along Low-Gradient Meadows

A few basins in central Nevada (such as Indian Valley and Lebeau) possess a number of very large, low-gradient meadow complexes (fig. 1.7). Although their valley floors may exhibit zones of sediment transport and deposition not all that different from those found in Marshall and Corcoran Canyons (fig. 3.10), the spatial scale over which the meadows exist leads to differences in the processes that govern valley entrenchment. The differences are significant enough that they must be considered separately from those previously discussed when developing management strategies for meadow complexes.

To date, the most extensively studied valley of this kind is within the Indian Valley basin (fig. 3.11), a headwater drainage to the Reese River (fig. 1.7). While the remainder of this discussion primarily focuses on Indian Valley, the results can be applied cautiously to similar meadow/valley systems, including those found farther downstream along the Reese River (fig. 2.1).

The most distinctive features along the valley floor of Indian Valley are a series of discontinuous gullies. The term "discontinuous" refers to the fact that the entrenched valley segments are not interconnected. Rather, the gullies terminate downstream in fan-shaped deposits that grade smoothly onto the valley floor. In contrast, the upstream terminus is characterized by a prominent headcut that often exceeds several meters in height (fig. 3.12a). Between the up- and downstream termini, the character of the trench changes in a semi-systematic manner. For example, one intensively studied gully (fig. 3.13) is approximately 2.5 km in length. Within upstream areas, several subparallel trenches are tributaries to the main trench and each ends upstream in a headcut (fig. 3.13). The main trench is rectangular in shape and is up to 4 m deep and 30 m wide. Trench width and depth both decrease downstream until reaching the

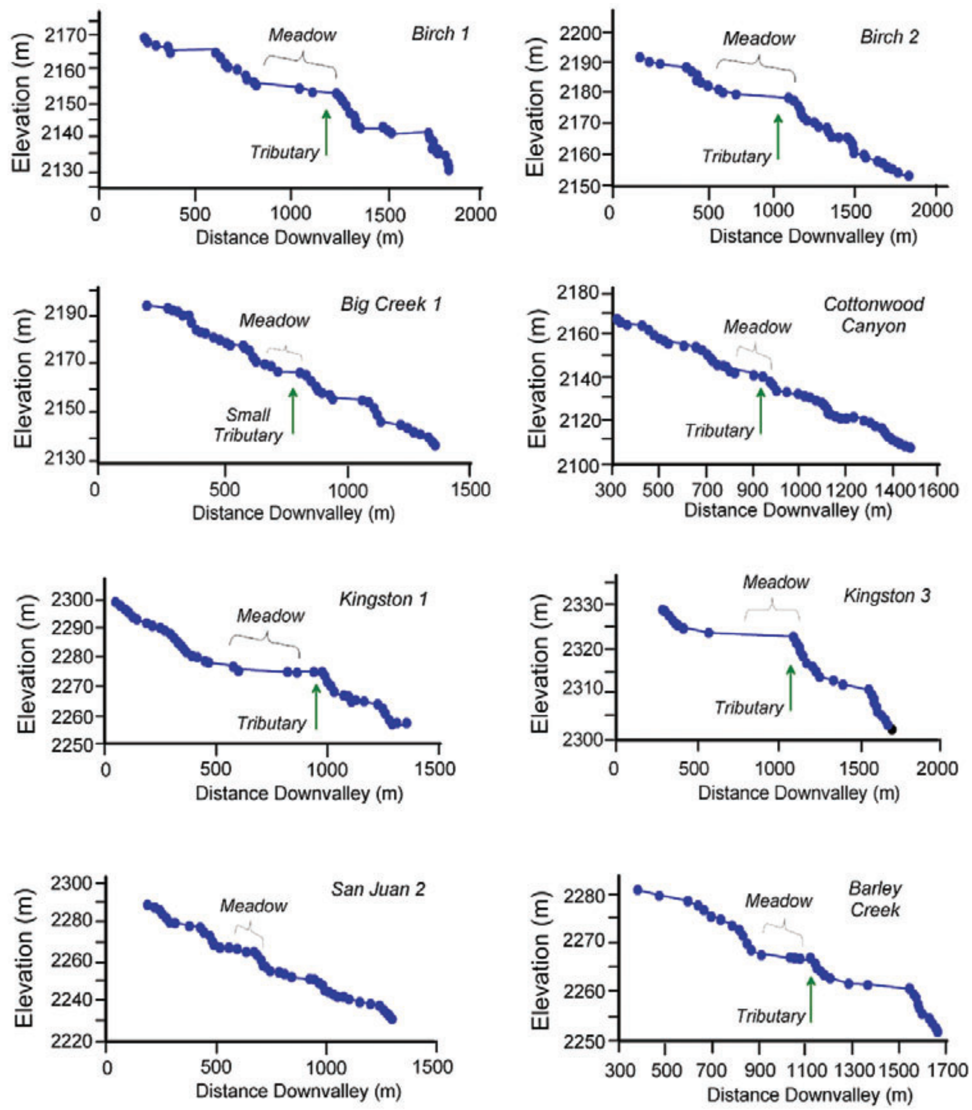


Figure 3.10. Down-valley profiles measured for selected upland drainage systems in central Nevada. Most wet meadows are located on wide, low-gradient reaches of the valley floor. See fig. 1.7 for meadow locations.

Figure 3.11. Aerial photograph of the Indian Creek valley showing the spatial distribution of wet meadows (circled). Entrenched reaches, generally located between meadows, are associated with zones of sediment transport.

unincised segment of the valley floor at the trench mouth. Throughout the incised reach, a stream channel is found on the trench floor. Along upstream segments of the trench, the channel is characterized by perennial flow, is bordered by well-defined floodplains and terraces, and is fine-grained (fig. 3.12c). Downstream, flow changes from intermittent to ephemeral and the size of the bed material increases until it is dominated by cobbles (figs. 3.12b and d). The shape of the stream channel also changes down-valley from a bed that exhibits deep, well-defined pools that are connected by narrow and much shallower runs to a relatively wide, featureless channel floor that encompasses most of the trench. Systematic variations in vegetation also occur in the downstream direction; upstream, the floodplain and terrace

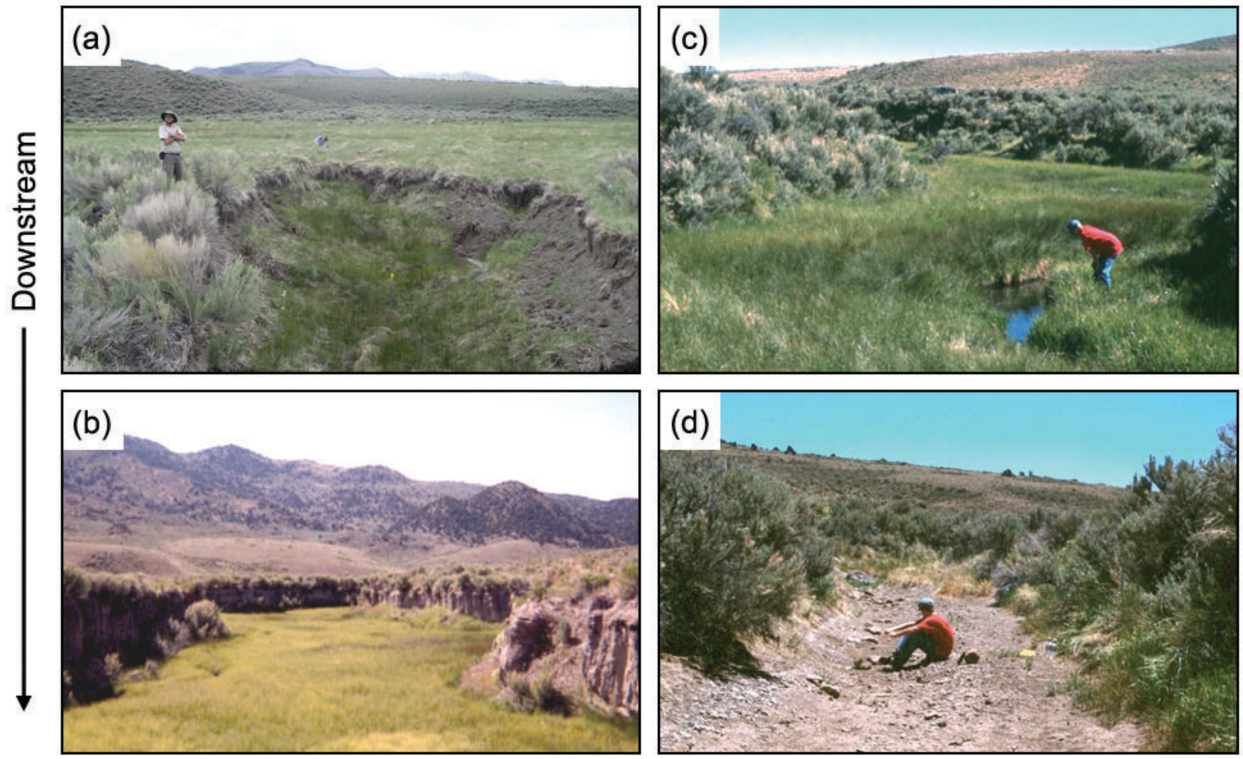


Figure 3.12. Downstream changes in channel morphology along a discontinuous gully in Indian Creek valley. (a) Upstream headcut; (b) incised trench containing high water table and strip meadows; (c) incised trench located downstream of (b); (d) most downstream reach that is dry and characterized by renewed deposition.

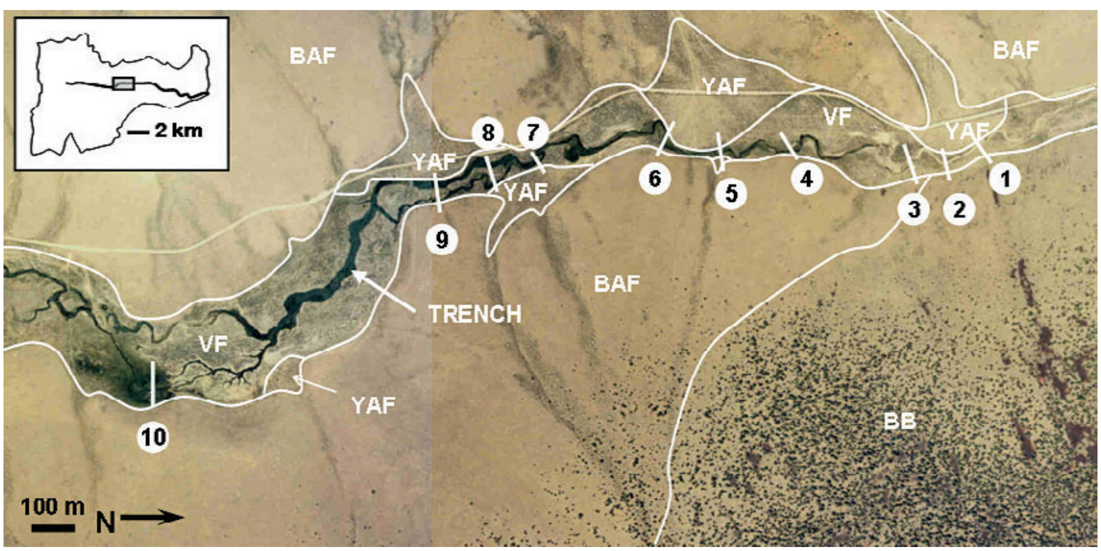


Figure 3.13. Aerial photograph of studied discontinuous gully system. Note that some gully headcuts are oriented at nearly right angles to the valley slope, suggesting erosion follows the direction of groundwater flow. Geomorphic units: VF = valley floor; TRENCH = incised trench long valley; YAF = young alluvial fans surface; BAF = older, bouldery alluvial fan surface; BB = basalt bedrock near surface associated with Black Mountain (northeast corner of photo). Groundwater measurements and vegetation surveys were made along transects (1 through 10). Index map shows study location and shape within the basin. See fig. 1.7 for basin location.

surfaces are covered by wet meadow species that creat strip meadows along the trench floor (fig. 3.12c). Downstream, dry meadow (or drier-end) species are dominant (figs. 3.12b and d).

The interactions and importance of surface- and groundwater flow to headcut migration in the Indian Valley meadows were analyzed by examining groundwater flow conditions in the vicinity of one headcut over a period of approximately five years, extending from 2002 to 2007 (fig. 3.14). The data

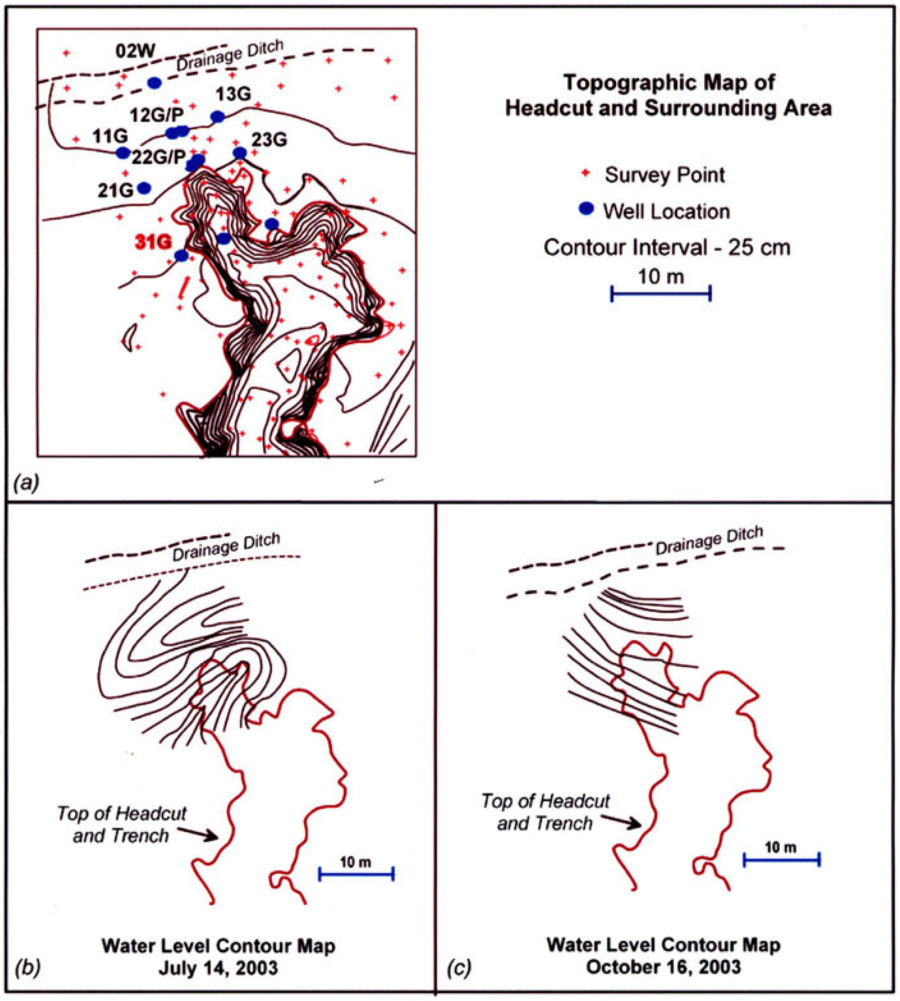


Figure 3.14. (a) Topography of an instrumented headcut in Indian Creek valley. Contour interval is 25 cm; (b) groundwater table on July 14, 2003; (c) groundwater table on October 16, 2003. The black arrow points to the top of the trench. Water table contours are based on measurements from 12 wells, shown in (a).

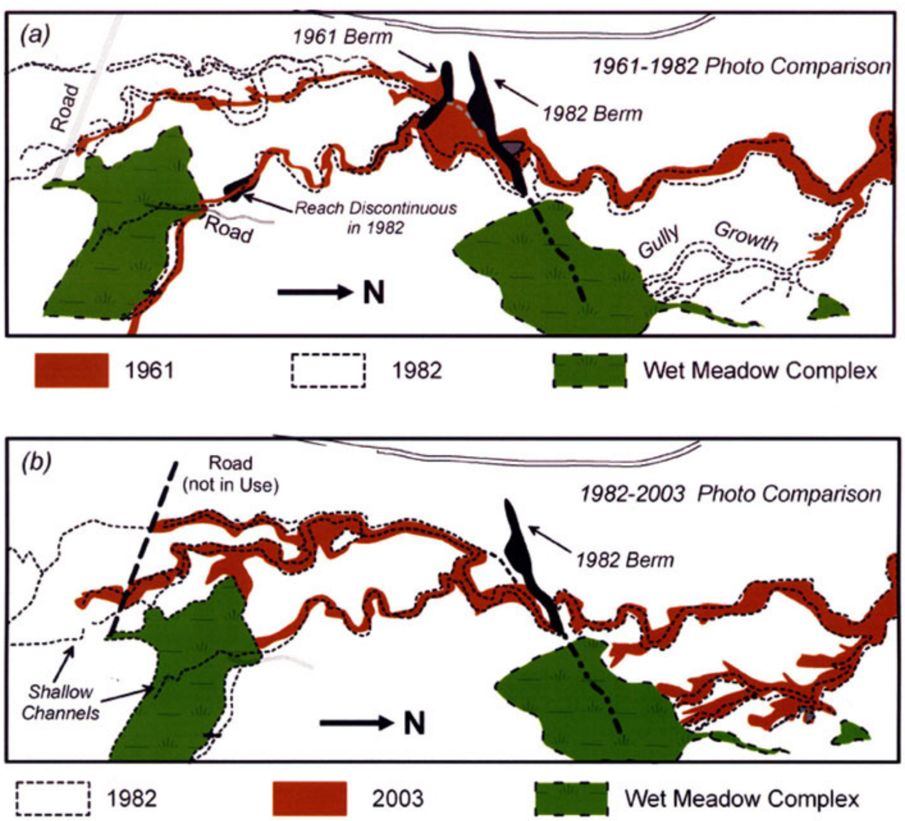


Figure 3.15. Extent of the discontinuous gully system in Indian Creek valley in 1961, 1982, and 2003. (a) Gully extension primary occurred between 1961 and 1982; (b) gully extension between 1982 and 2003 is thought to have primarily occurred during the 1982/1983 flood, the largest recorded during the past century.

Figure 3.16. Fracture exposed in the wall of a headcut in Indian Creek valley. These types of fractures presumably influence the dimensions of bank failure blocks and the rate at which headcut advancement can occur.

suggest that groundwater plays an extremely important role in controlling the nature and rate of headcut advancement. Indicators of the importance of groundwater on headcut migration are: (1) the amphitheater-shaped geometry of the headcuts, which is often used as an indicator of erosion by groundwater processes; (2) seepage from the headcut face and trench walls, particularly during the spring and early summer months; and (3) the cross-valley orientation of some tributary trenches that are aligned semi-parallel to the general direction of groundwater flow rather than with the predominant direction of surface runoff (fig. 3.15b).

Groundwater appears to influence headcut advancement by initiating mass wasting processes. It is well known that rising water tables and increased pore pressure tend to reduce the strength of alluvial materials, initiating episodes of bank failure (Thorne and Lewin 1979; Thorne 1982; Simon and others 1999). It can be hypothesized that observed slope failures along Indian Valley and other similar valleys correspond to wet periods of enhanced seepage and spatially, to zones of flow convergence as governed by the local groundwater flow system. The predominant mechanism of headcut advancement appears to be bank failure initiated by temporal and spatial variations in groundwater flow and subsequent weakening of the bank material strength. This suggestion is supported by modeling data generated by Johnson (2004). Using a program called Slope/W by Geo Slope International, he found that bank stability decreased with increasing head levels at the headcut instrumented in Indian Valley (fig. 3.14) and that seasonal slope failure was likely during the late spring when local groundwater levels were at their highest.

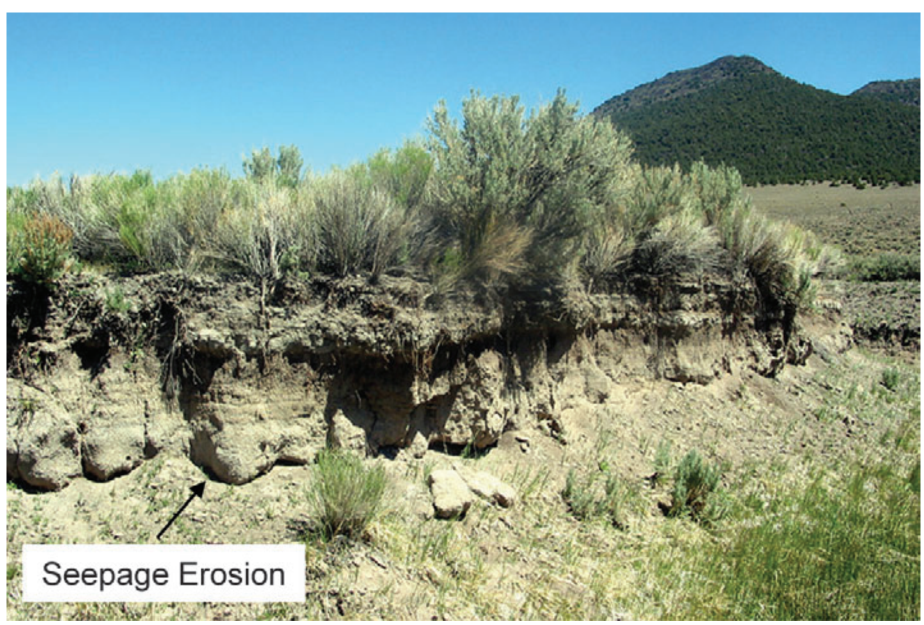


Figure 3.17. Wall of trench located downstream of the headcut shown in fig. 3.16. The eroded "alcove" positioned along the base of the bank was likely caused by groundwater as it emerged from the valley fill. This type of undercutting often leads to bank failure.

Montgomery (1999) found that headcut advancement in California's Tennessee Valley also was tied closely to groundwater-related bank failure mechanics. He argued that advancement resulted from development of vertical fractures during periods of drying (desiccation) and subsequent failure of the blocks of bank materials that were defined by the fractures as water levels rose. The annual rate of headcut advancement was dependent on the distance of the fractures from the bank face because only one block would fail during an annual wetting and drying cycle. The importance of fracture formation to headcut advancement within Indian Valley appears to be variable. Some headcuts clearly developed pressure-release fractures during desiccation, and the size and rate of failure was controlled by fracture dimensions (fig. 3.16). In contrast, fractures were not observed at other headcuts, and failed blocks of bank material exhibited a rotational movement. Field observations suggest that differences in fracture development were associated with variations in the grain size distribution of the bank material, with fractures forming in finer-grained sediment composed of expandable clays.

The upstream migration of headcuts by the groundwater-enhanced failure mechanism just described can continue only if the failed bank material is removed from the base of the slope. Until the debris is removed, the slope is stabilized by the buttressing effects of the failed sediment (Carson and Kirkby 1972). Although seepage was observed to remove some of the basal bank material, most material was likely removed by small- to moderate-sized surface flows. Thus, headcut advancement involves both a groundwater component that initiates bank failure and a surface water component that removes failed bank material. During low to moderate runoff years, headcuts tend to precede up-gradient, parallel to groundwater flow because elevated groundwater levels are most likely to lead to headcut instability and failure, all other factors being constant. The development of the headcut, then, is a self-enhancing process because once it begins to form, the trench will create a convergence of surface- and groundwater flow, both of which will promote headcut advancement. That is, trench development creates the conditions that are conducive to further valley incision and upstream headcut migration.

Another means through which groundwater influences headcut migration is known as seepage erosion or "sapping." Sapping refers to the application of an upward force by groundwater on individual particles, which reduces their effective particle weight and facilitates particle entrainment (Howard and McLane 1988). Over time, entrainment and transport of particles produces a hollow or alcove in the trench wall that leads to bank failure by mass wasting processes (fig. 3.17). Sapping is exacerbated by high rates of groundwater discharge, which are associated with highly permeable materials, steep groundwater gradients, and layered geologic materials with contrasting hydraulic properties that encourage horizontal flow.

A closely related process to sapping is called "piping," a phenomenon that involves the enlargement of existing macropores and cavities by groundwater flow (Anderson and Burt 1990). The formation of pipes is generally associated with burrows, decaying roots, or other openings created by plants and animals. The process tends to be particularly prevalent in clay-rich soils characterized by shrink-swell processes, which amplify the rate of erosion (Heppell and others 2000). Like sapping, piping can locally undermine the trench wall and lead to slope failure. Piping is so prevalent in Corcoran Canyon that pipe collapse and the subsequent removal of the failed bank material by overland flow is the dominant mechanism of meadow degradation. Both piping and sapping processes were observed along the trench walls of Indian Valley. However, the distribution of pipes and undermined banks resulting from seepage erosion is not temporally and spatially extensive enough to account for all of the advancement of headcuts observed within Indian Valley. Nonetheless, sapping and piping are extremely important processes because they can erode fine-grained particles from beneath many types of headcut treatments that are constructed of rock, logs, and other materials, rendering the treatments ineffective in a short period of time.

Figure 3.18. Headcut associated with a shallow, discontinuous channel within a wet meadow of Indian Creek valley. Headcut migration occurs by plunge-pool erosion and undermining of the headcut face during surface runoff. Photograph taken in June 1996 during the falling limb of the annual snowmelt event.

The short-term rates of headcut advancement within the gullies monitored in Indian Valley were on the order of 1 m/year. The comparison of aerial photographs between 1961 and 2003 show that headcuts periodically have advanced much more rapidly than was measured in the field during the observation period (fig. 3.15). It is unlikely that such rapid rates of migration (particularly between 1961 and 1982) could occur by means of the groundwater-induced failure mechanism previously described. Thus, it is thought that rapid headcut advancement occurs by means of repeated plunge-pool erosion and undermining of the headcut, followed by the failure and rapid removal of the material during major runoff events such as those in 1973, 1975, 1978, or 1983/1984 (fig. 3.13). This argument is extremely important because it suggests that the mechanisms of headcut erosion differ between periods of "average" and "high" runoff and that while the rates of advancement are driven by slower-acting groundwater processes during periods of average runoff, they are controlled by surface flows in the latter. Management strategies aimed at reducing the rate of headcut advancement need to consider both sets of processes to be effective.

A question of significant concern from a management perspective is: how do the large, advancing headcut systems initially form? Montgomery (1999) argues that within California's Tennessee Valley, abrupt channel heads are created once incision by entrainment of individual particles exposes the soil B-horizon. In the B-horizons, the soil structure, including vertically oriented fractures, allows for the repeated failure of blocks of soil from a near-vertical face. The abrupt break in topography can then extend deeper during upstream headcut advancement. Both field and aerial photographic data show that, in addition to the large gully systems, the valley floor within the wet meadow complexes of Indian Valley exhibit two distinct types of shallow, discontinuous channels. One type of channel is fed by overland flow, which enters along a uniformly graded slope. Erosion and incision along these channels occurs by the removal of individual particles by runoff. Channels of the second type tend to be slightly deeper, and their beds are characterized by one or more small headcuts developed below the zone of rooting (fig. 3.18). Headcut migration tends to occur by bank failure along the headcut face. Assuming that these two types of discontinuous channels represent an evolutionary sequence that culminates in the large discontinuous gullies, the development of headcuts along the stream in Indian Valley would appear to be similar to that suggested by Montgomery (1999). In these cases, incision

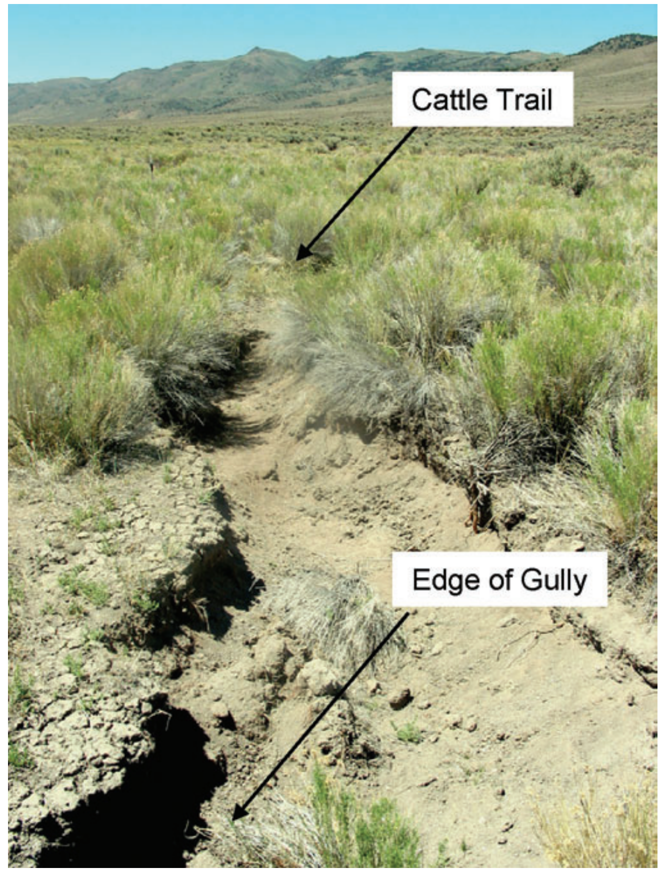


Figure 3.19. Cattle trail leading to the edge of a headcut in Indian Creek valley. The spatial correlation between cattle trails and gullies suggest that, in some cases, overland flow is concentrated within the trail and is capable of eroding the valley fill.

Figure 3.20. Spring, or blowhole, on the valley floor of Indian Creek valley. These springs create shallow channels that may eventually be enlarged to create larger gully systems.

begins with erosion of the valley floor by the entrainment of individual particles and evolves into a gully once incision has reached a sufficient depth to allow for block failure from a near-vertical face. Once developed, the self-enhancing nature of the headcuts caused by the convergence of surface and groundwater flow allows headcuts to grow deeper as they advance upstream.

Incision of the valley floor by particle entrainment and headcut advancement are both promoted by saturated conditions. This is likely to explain the tendency for shallow channels to be concentrated within wet meadows as opposed to drier areas of the valley floor. In contrast, re-deposition of sediment downstream within the trench or on the valley floor is likely to be associated with a loss of stream power (less influent flow) and an increase in suspended sediment concentration.

The gully development and expansion that was previously described requires the initial erosion of the valley floor by overland flow. The ability of surface flows to entrain particles is strongly governed by the area's microtopography and vegetation characteristics. Any activity that promotes flow concentration or reduces vegetative cover (or stem density/roughness) tends to promote particle entrainment. In Indian Valley, a large number of shallow channels and headcuts are fed by minor (<20 cm deep) linear depressions that are devoid of significant vegetation. These depressions are associated with cattle trails, suggesting that the initial erosive process required for gully development could be promoted by livestock (fig. 3.19). Other activities such as roads and diversion structures that were intended to reduce channelized erosion also created zones of concentrated flow. Thus, these wet meadows appear to be particularly sensitive to anthropogenic activities, including the installation of rehabilitation structures, which divert flow to other locations of the valley floor in an attempt to reduce erosion in an existing gully. However, natural processes also can initiate shallow channel systems. One such process is the development of vertical springs or blowholes, in which water under extreme pressure rises to the surface of the meadow and flows down-valley, creating a channel system (fig. 3.20).

Groundwater measurements along the instrumented trench of Indian Valley show that gully heads are characterized by effluent flow associated with groundwater convergence on the headcut (fig. 3.14). Downstream, the in-flow of water from the subsurface becomes seasonally variable before eventually changing to a condition in which water is lost from the channel throughout the year. Thus, sediment deposition at the mouth of the gullies appears to be related to a change in the relations between the surface and groundwater flow systems in the vicinity of the trench. In the case of the large, deep gullies, these relations are strongly controlled by regional physical features such as the nature of the underlying bedrock and valley morphology (see discussion on Indian Valley hydrology in the following section and Jewett and others 2004), which produce zones of downward groundwater flow. However, the observed influent and effluent conditions also are related to the evolution of the gully. As headcuts advance upvalley, groundwater levels downstream of the headcuts drop, eventually leading to a loss of water through the trench floor and to sediment deposition (Jewett and others 2004).

Channel Avulsion

The majority of meadow complexes found in central Nevada are dominated by fine-grained, often organic sediments. Locally, these fine-grained sediments are buried by thin (<1 m thick) sand and gravel deposits (fig. 3.21). In some cases, the sands and gravels completely fill a paleochannel and spill onto the valley floor as lobate, convex-up accumulations. In other locations, the sands and gravels can only be found as convex-up bars. Laterally, the deposits are discontinuous, thinning toward the margins and in the downstream direction.

Field and aerial photographic data suggest that these coarse-grained deposits were produced by avulsion. Avulsion is a process by which the channel is abruptly relocated from one position on the valley floor or floodplain to another. In a review of avulsion processes, Jones and Schumm (1999) subdivided avulsions into four groups based on the factors that lead to channel relocation. However, while one avulsion process may dominant the system, others may contribute to channel relocation and, within a given region, avulsion may be caused by more than one set of factors. Therefore, care must be taken when attributing causes of avulsion for a particular stream. Nonetheless, avulsion within meadow complexes of central Nevada appears to be related to clogging of the channel and loss of flow capacity as a result of stream bed aggradation. The loss of channel capacity leads to overbank flooding and the scouring of a new channel system that bypasses the aggraded reach. This process is well illustrated by a 1983 event that occurred along Cottonwood Creek on west side of the Toiyabe Range (fig. 1.7).

In Cottonwood, gravel-sized sediment filled a short-reach of the axial channel at the upstream end of a wet meadow complex (fig. 3.22). The coarse sediment was then ramped onto the meadow surface by overbank flood waters, creating several gravel bars that were oriented at about a 35° angle from the axial channel alignment (fig. 3.22). The bars were approximately 15 m long, 5 m wide, and buried finer-grained meadow sediments. Flow that emanated from around the bars coalesced downstream in a shallow depression in the meadow surface and rapidly eroded a narrow, approximately1.5 to 3 m deep channel into the valley fill (fig. 3.22). The newly cut channel allowed flows from upstream to bypass the aggraded reach, and a piece of the pre-existing channel down-valley of the sediment-clogged stream section remained as an abandoned channel (fig. 3.22). Over the next several years, the newly cut channel continued to incise and widen to accommodate the incoming flows from upstream. Comparison of channel photos with cross sectional profile data indicated that much of the channel enlargement occurred between 1997 and 1999 (when the first cross-section was surveyed), presumably during the relatively high runoff year of 1998 (fig. 3.22).

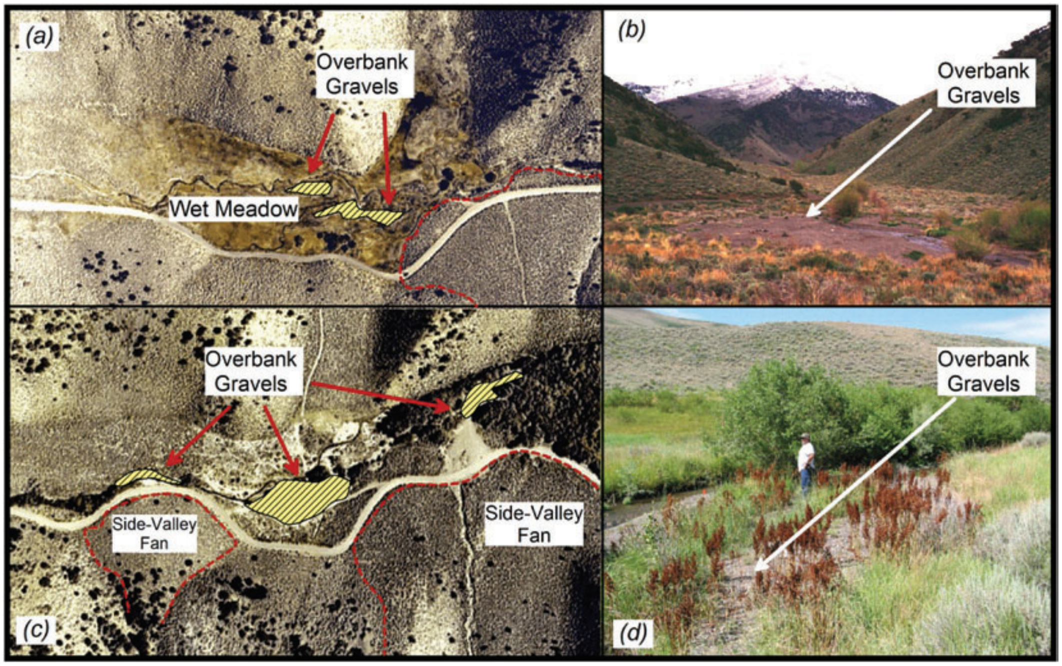


Figure 3.21. Course gravel deposits located on the valley floor of Kingston (a, b, c) and Birch (d) Canyons. These deposits are thought to have formed during channel filling and avulsion that resulted from the localized influx of coarse-grained sediment. Flow in (a) and (b) is from left to right.

A similar process likely occurred within Birch 2 meadow (fig. 1.7). However, it differed from the avulsion described for Cottonwood in that overbank flood waters flowed down-valley into an existing spring channel that was dominated by fine-grained sediment. The spring channel was subsequently converted into the axial drainage system through erosive processes that deepened and widened the original channel.

The frequency at which avulsion occurs varies from one meadow to another. However, it is clear that channel avulsion is a fundamental process associated with meadow development. For example, older bars partially covered by fine-grained sediment are visible as topographic highs within the Cottonwood meadow. In addition, the valley fill within Kingston 3 meadow (fig. 1.7) exhibits thin, laterally discontinuous sand and gravel lenses that are interspersed with finer-grained sediments (fig. 3.23). These lenses presumably represent the deposition of sand and gravel during channel avulsions, followed by burial with silts and clays during overbank flooding. Radiocarbon (C-14) dates obtained from organic materials in the cores show that these gravel deposits date back at least 8000 years BP, indicating that avulsion has been an integral part of meadow aggradation and development throughout the Holocene.

The idea that channel bed aggradation leads to avulsion may seem to contradict suggestions that channels within the upland basins of central Nevada are sediment starved and tend to incise. Both hypotheses can be correct because aggradation that is associated with avulsion is produced by the rapid, temporary influx of coarse sediment to the drainage network. This aggradation represents a short-term condition that is superimposed on a longer-term tendency for channel incision. In Cottonwood, the near instantaneous influx of gravel-sized sediment to the meadow was created by rapid remobilization of material stored behind a series of upstream beaver dams that were breached during the high flows of 1983. Other potential sources of sediment that may rapidly deliver coarse sediment to the drainage network are mass wasting events (such as landslides), localized trenching of side-valley fans during episodes of extreme runoff, and/or the dissection of roads by runoff (fig. 3.24).

Stratigraphic and cartographic data show that avulsions are primarily limited to meadows; reaches of the stream channel without meadows show little evidence of past avulsion episodes (Miller and others 2001). This observation results from the tendency of sediment that is rapidly flushed into the drainage network to be redeposited within the meadow complex. Aggradation within the meadow is probably induced in large part by changes in channel gradient that often occur as a result of long-term aggradation of the valley floor upstream of side-valley alluvial fans and other valley constrictions. Jones and Schumm (1999) argue that aggradation and subsequent avulsion also may be related to encroachment of riparian vegetation, which leads to a loss of channel capacity, an increase in channel roughness, and a reduction in flow velocities. The association of localized aggradation and avulsion in meadow areas that are heavily overgrown by willows, such as in Kingston Canyon and Birch Creek (fig. 3.25), suggests that riparian vegetation may contribute to aggradation in some upland watersheds.

Summary

Channel incision, gully formation, and avulsion have significantly affected meadow complexes in central Nevada. The most widespread impacts are associated with incision, which has been observed in most upland meadow complexes in the region. The mechanisms of incision vary as a function of the underlying bedrock and grain size of erodible material. Incision by the entrainment and transport of individual grains occurs along reaches that are characterized by loose,

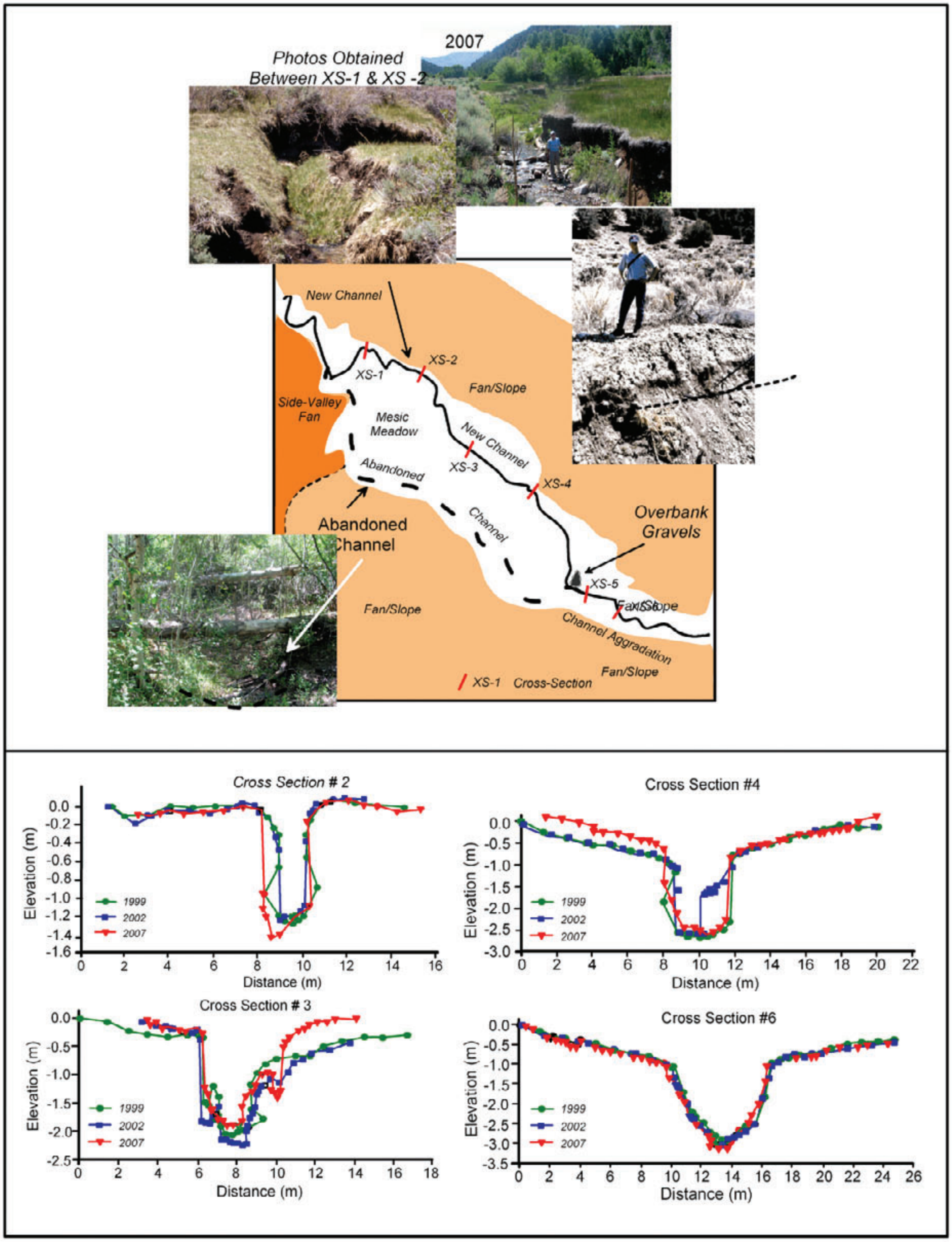


Figure 3.22. Channel changes associated with an avulsion that occurred in 1983 along Cottonwood Creek. Upstream reaches of the abandoned channel were filled with sediment that was derived from behind failed beaver dams. Aggradation within the channel led to overbank flows, deposition on the valley floor, and downstream incision of a new channel. Cross sections illustrate changes in the resulting incised channel from 1999 to 2007.

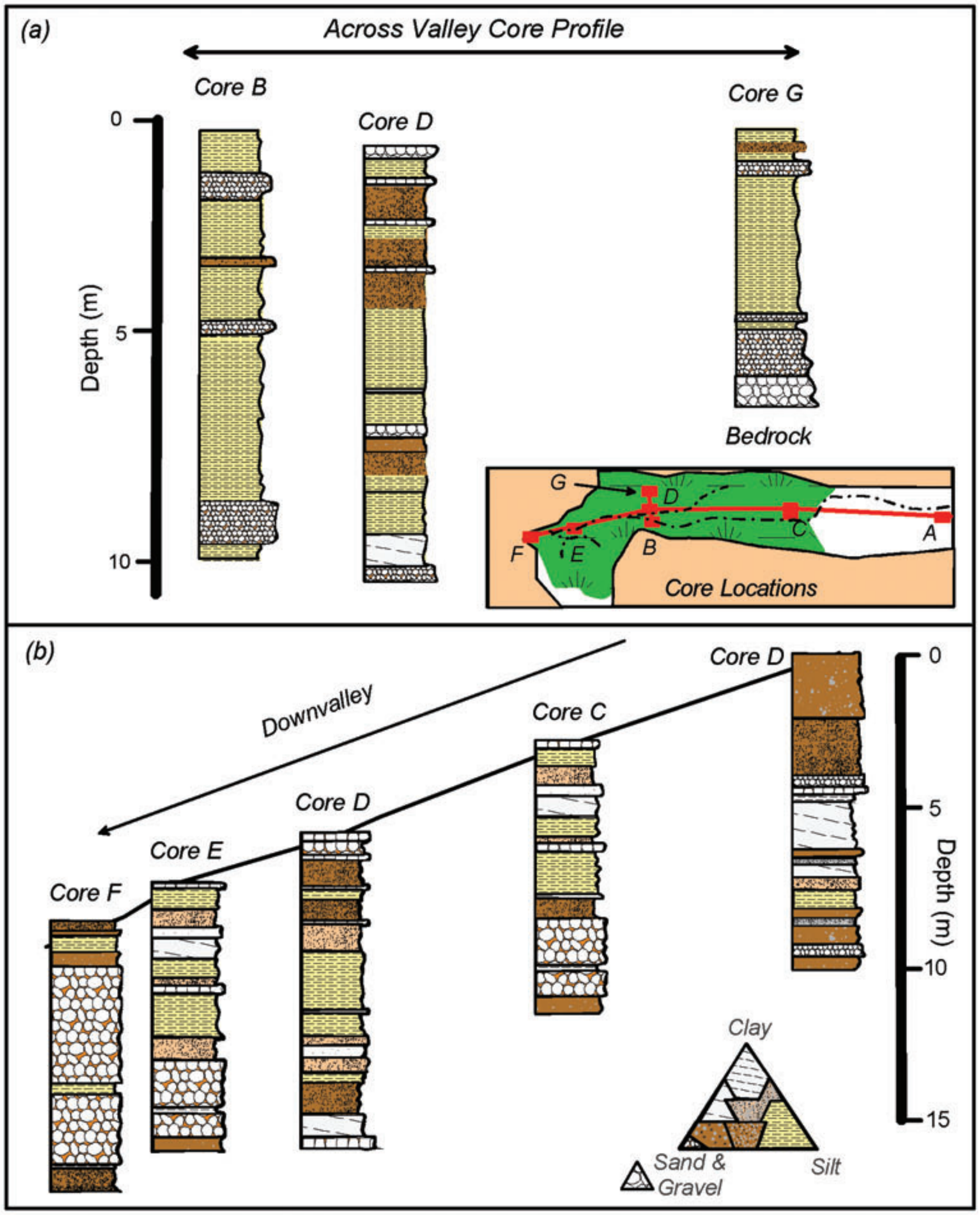


Figure 3.23. Stratigraphic units observed in cores extracted from Meadow #3 in Kingston Canyon. The spatially discontinuous nature of the sand and gravel units suggests that they were formed by avulsion processes similar to those observed along Cottonwood Creek.

coarse-grained sediment; whereas incision by knickpoint formation and migration occurs along stream segments that are characterized by fine-grained, more cohesive sediments. In many instances, incision is initiated by a drop in base level along a convexity in the longitudinal profile that is created by a side-valley alluvial fan, or by deposition upstream of a bedrock valley constriction. Once initiated, incision progresses upstream as the channel adjusts to the lowered base level.

Gully formation is predominantly limited to valley systems without an integrated drainage system. Once gullies have formed, the rate of headcut advancement varies as a function of the overland flow intensity. During extreme events, gully formation occurs by means of repeated plunge-pool erosion and undermining of the headcut, followed by failure and rapid removal of the failed bed and bank material. During years characterized by low to moderate runoff events, headcut advancement is controlled primarily by groundwater sapping processes. Therefore, to be effective, management strategies that are aimed at reducing the rate of headcut advancement need to consider processes that occur during both low flow and high flow years. In addition, observations from Indian Valley indicate that meadow complexes are sensitive to activities that may concentrate flow on the surface, including trails created by livestock.

Channel avulsion is primarily restricted to low-gradient, meadow environments and is induced by the temporary influx of coarse sediment, which causes localized channel aggradation and filling. The resulting reduction in channel capacity (cross-sectional area) forces water over the channel banks and results in valley entrenchment at a new location within the meadow complex. In some cases, the overbank waters are diverted into smaller spring channels, which are subsequently converted into the axial drainage system. Data from recent avulsions suggest that it may take a few decades for an incised channel produced by avulsion processes to acquire the morphology that is typical of channels up- or downstream of the site.

Figure 3.24. Potential sources of temporary sediment influx to axial drainage systems in the upland watersheds of central Nevada. (a) Trenching of previously unincised hillslope hollows during extreme runoff events; (b) the trenching of roads, in this case, Slaughterhouse Canyon in 1997; (c, d) the breaching of beaver dams and the subsequent erosion of stored sediment.

Figure 3.25. Gravel deposition and channel accretion along segments dominated by streamside willows.

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