BioScience Advance Access published March 26, 2014

Using Beaver Dams to Restore Incised Stream Ecosystems

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Biogenic features such as beaver dams, large wood, and live vegetation are essential to the maintenance of complex stream ecosystems, but these features are largely absent from models of how streams change over time. Many streams have incised because of changing climate or land-use practices. Because incised streams provide limited benefits to biota, they are a common focus of restoration efforts. Contemporary models of long-term change in streams are focused primarily on physical characteristics, and most restoration efforts are also focused on manipulating physical rather than ecological processes. We present an alternative view, that stream restoration is an ecosystem process, and suggest that the recovery of incised streams is largely dependent on the interaction of biogenic structures with physical fluvial processes. In particular, we propose that live vegetation and beaver dams or beaver dam analogues can substantially accelerate the recovery of incised streams and can help create and maintain complex fluvial ecosystems.

Keywords: ecosystem restoration, stream restoration, conservation, beaver, Castor canadensis

Throughout many regions of the world, channel incision is a widespread environmental problem that has caused extensive ecosystem degradation (Wang et al. 1997, Montgomery 2007). The defining characteristics of an incised alluvial stream are a lowered streambed and disconnection from the floodplain (Darby and Simon 1999). The resulting changes in physical habitat degrade stream ecosystems (Shields et al. 1994, 2010). Ample evidence in the geological record indicates that channel incision occurs naturally and may be related to changes in climate (Bryan 1925, Elliot et al. 1999). However, a great many instances of channel incision have been shown to be caused by or to be correlated with changes in land use (Cooke and Reeves 1976, Montgomery 2007). Many of these changes are also contemporary with the widespread extirpation of beaver (*Castor canadensis*) in the nineteenth century (Naiman et al. 1988).

In addition to lowered streambed elevation and disconnection from the floodplain, common physical effects of alluvial incision include lowered groundwater tables, the loss of wetlands, lower summer base flows, warmer water temperatures, and the loss of habitat diversity. Biological effects include a substantial loss of riparian plant biomass and diversity and population declines in fish and other aquatic organisms (for a review, see Cluer and Thorne 2014).

Understanding how the ecology of an incised stream changes over time is essential for assessing recovery potential. However most incision–aggradation models describe only those geomorphological changes on the basis of relationships between sediment transport and hydrology. The role of living organisms is generally minimized, especially for beaver, live vegetation, and dead wood (Schumm et al. 1984, Simon and Hupp 1986, Elliot et al. 1999). The absence of beaver in such models is particularly notable, given their widely recognized role in shaping stream ecosystems (Naiman et al. 1988, Gurnell 1998, Pollock et al. 2003, Burchsted et al. 2010). More recently, incision–aggradation models have included floodplain complexes as an additional and ecologically desirable hydrogeomorphic stage that occurs in some fluvial ecosystems (see Cluer and Thorne 2014). Restoration of complex floodplains is important because such habitat is essential for the maintenance of biological diversity, including commercially important species, and for providing other important ecosystem services, such as flood control, groundwater recharge, and carbon storage (Grosholz and Gallo 2006, Westbrook et al. 2006, Jeffres et al. 2008, Wohl 2011, Bellmore et al. 2012, Cluer and Thorne 2014, Polvi and Wohl 2013).

In this article, we propose an alternative and more comprehensive view of stream evolution as an ecological—or more precisely, *ecogeomorphic*—process (*sensu* Wheaton et al. 2011). We provide a conceptual model for incised stream evolution that describes stream succession as a process dependent on the interaction of living organisms with hydrologic and sediment dynamics. We believe that such a model is consistent with recent findings concerning the role of biogenic features, such as wood and beaver dams, in

BioScience XX: 1–12. Published by Oxford University Press on behalf of the American Institute of Biological Sciences 2014.
doi:10.1093/biosci/biu036
Advance Access publication XXXX XX, XXXX

shaping natural fluvial ecosystems in North America prior to European colonization (Walter and Merritts 2008, Polvi and Wohl 2013, Wohl 2013). Within this framework, we illustrate how beaver dams and live vegetation can accelerate the recovery of incised streams and also how beaver dam analogues (BDAs) can accelerate recovery by mimicking many of the functions of beaver dams (BDAs are described in Pollock et al. 2012). To this end, we first describe the physical and biological processes that control the occurrence and rates of incision and aggradation. We then describe current incision–aggradation models and propose revisions to these models that explicitly incorporate beaver dams, BDAs, and vegetation. We restrict our conceptual framework to low-gradient alluvial valleys, primarily because this is where beaver typically build channel-spanning dams but also because this is where stream ecosystems attain their highest level of ecological functionality. Although they are not the focus of this study, we also note the analogous and divergent roles of another historically common channel-spanning biogenic structure: large wood (see Wohl 2011, Polvi and Wohl 2013).

Thus, we advocate a novel view of incision-prone streams and adjacent floodplains as fluvial ecosystems that undergo a predictable series of phases, analogous to successional processes in upland ecosystems and defined by the interaction of biological and physical processes. We conclude that restoration efforts can exploit such interactions to accelerate the aggradation and recovery of incised streams. This process-based approach differs somewhat from conventional restoration approaches, in which the goal is often to design stable channels that efficiently route water and sediment inputs downstream and in which facilitating aggradation for the purposes of creating or reconnecting complex floodplain habitat is not considered (e.g., Rosgen 1996). Our proposed conceptual model is based on over a decade of scientific investigation into the effects of vegetation, beaver dams, and BDAs in incised stream ecosystems (Pollock et al. 2003, 2007, 2012).

Physical and biological factors affecting incision and aggradation rates

Whether natural or human induced, channel incision occurs when sediment transport increases or erosion resistance decreases such that the excavation rate of streambed sediment is faster than its replacement rate (Beechie et al. 2008). Conversely, aggradation occurs when bed material accumulates more rapidly than it is exported. This is classically represented by the simple mass balance equation:

$$\Delta S = I - O, \qquad (1)$$

where ΔS is the change in storage, I is sediment input, and O is sediment output. This equation is typically focused on bed material, which is commonly viewed as being controlled only by sediment and water. However, sediment retention mechanisms often include biogenic controls such as wood jams, floodplain vegetation, or beaver dams (Cluer and Thorne 2014, Polvi and Wohl 2013). Below, we review and summarize both the physical and the biological factors that control rates of sediment input and export, focusing on the processes important for initiating sediment retention and aggradation.

Physical factors

Sediment inputs are composed of both bed load and suspended load, and aggradation rates of incised channels are affected by both components. For bed load, the basic relationship between streamflow and sediment transport is commonly conceptualized with Lane's balance (Lane 1955; see also Dust and Wohl 2013), which states that a dynamic equilibrium or balance can exist between stream power and sediment discharge (figure 1a):

$$Q_S d_{50} \propto QS, \qquad (2)$$

where Q_S is sediment discharge, d_{50} is the median sediment size, Q is the amount of discharge of water, and S is the streambed slope. Incision or degradation occurs when there is a significant decrease in the size or amount of sediment or an increase in the slope or amount of discharge (figure 1a).

Stream power per unit width (ω), which is related to discharge and the slope (the right side of equation 2), is also used to model aggradation rates and is given by the equation

$$\omega = \gamma QS/w, \qquad (3)$$

where γ is the specific weight of water, and w is the channel width. This equation suggests that increasing channel width will reduce ω, which should increase aggradation rates. In contrast, decreasing channel width usually deepens the stream, which will increase ω. This deepening can increase sediment transport capacity, causing a channel to incise (figure 1a). Once the channel has incised, ω can be reduced if stream width is increased or the slope is reduced. Therefore, incised streams do not easily aggrade until the incision trench has widened, ω declines, and sediment transport capacity is reduced.

Although a reduction of stream power is often essential for aggradation to occur, other factors affecting aggradation rates are the quantity and size of sediment entering the stream (the left side of equation 2). In many cases, the vast majority of total input is transported as suspended load (Mapes 1969), and aggradation on floodplains inset within an incision trench may occur primarily through deposition of suspended load (e.g., Beechie et al. 2008). Moreover, much of the initial sediment supply within a reach may come from a widening of the incision trench, and this widening also increases the size of the excavated trench and, therefore, the volume of sediment needed for aggradation. Therefore, for substantial aggradation to occur, additional sediment must eventually come from upstream sources. Because most of the upstream sediment supply is typically suspended, increasing the aggradation rate may require a means of slowing

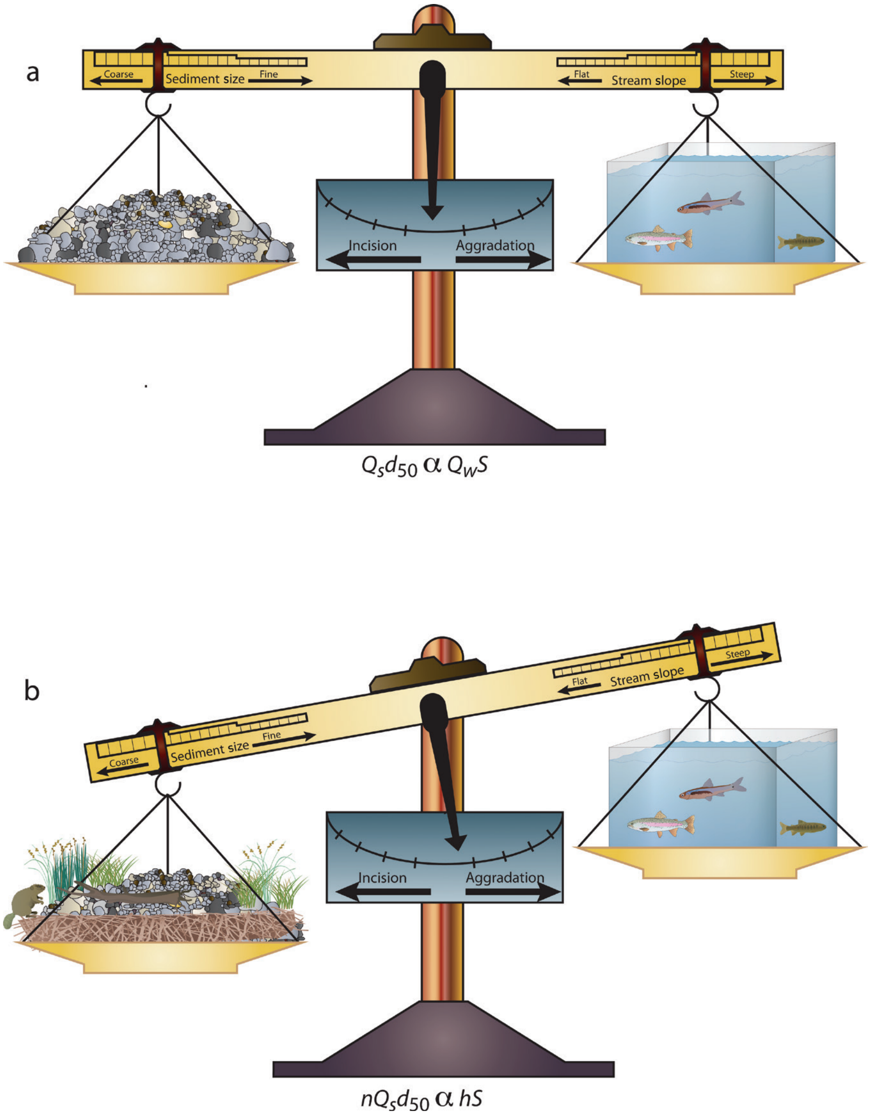

Figure 1. Lane's balance (a) describes how changes in sediment load, sediment size, slope, and discharge determine whether a stream system will aggrade or incise. Basic relationships among discharge, stream power, and velocity suggest that Lane's balance can be modified (b) to incorporate the effects of biogenic flow obstructions, such as beaver dams, vegetation, and large wood. Given sufficient sediment supplies, these should generally shift the balance toward aggradation. Source: Adapted from Lane (1955).

flow velocities enough to allow deposition of suspended sediments—especially on inset floodplains (this is discussed further in the following section).

Although we have described incision and aggradation as a simple linear response to a single perturbation, at the scale of a watershed, there can be multiple perturbations occurring at different times and in different locations within the watershed. Furthermore, the response of a particular reach can vary, depending on its position within the watershed and its intrinsic geomorphic nature, such as the valley width, valley slope, and alluvial composition. Such complex and nonlinear responses are described by channel-evolution, complex-response, and threshold models (e.g., see Graf 1979, Schumm et al. 1984, Darby and Simon 1999).

Biological factors

The preceding equations and mechanisms emphasize physical processes and do not incorporate biogenic factors that influence sediment transport or retention. On the basis of relationships among stream power, discharge, and velocity, Lane's balance can be recast (figure 1b) as

$$nQ_s d_{50} \propto hS, \qquad (4)$$

where n is Manning's coefficient, an empirically derived measure of the flow resistance provided by grain roughness, bed forms, or obstructions within a channel (Barnes 1967), and h is the average stream depth. Equation 4 suggests that increasing channel roughness can increase retention of both bed load and suspended sediment (figure 1b).

Suspended load deposition is a function of flow velocity and turbulence, and initiating deposition of a suspended load typically requires a significant decrease in flow velocity. In equation 4, suspended load transport can be altered by decreasing the slope or increasing roughness (n), either of which will reduce stream velocity and cause deposition of suspended sediment. Therefore, according to equations 3 and 4, biogenic features can influence both bed load and suspended load transport by changing the slope, roughness, or channel width, each of which can tip Lane's balance to the left and increase aggradation rates (figure 1b). For example, exclusion of cattle from the riparian area has been shown to allow vegetation to colonize the inset floodplain, thereby increasing channel roughness. This alone can reduce flow velocities, trap suspended sediment, and aggrade an incised channel at a rate of roughly 0.03 meters (m) per year (Beechie et al. 2008).

Other biogenic structures, such as beaver dams and logjams, have even more dramatic effects on flow resistance and sediment transport (Mutz 2000, Green and Westbrook 2009, Aberle and Järvelä 2013). Notably, aggradation rates at beaver dam sites are more than double those at comparable sites with vegetation alone (Pollock et al. 2007, Beechie et al. 2008). Beaver dams and large, channel-spanning wood jams increase roughness, reduce the slope, and increase channel width, all of which contribute to increased retention of

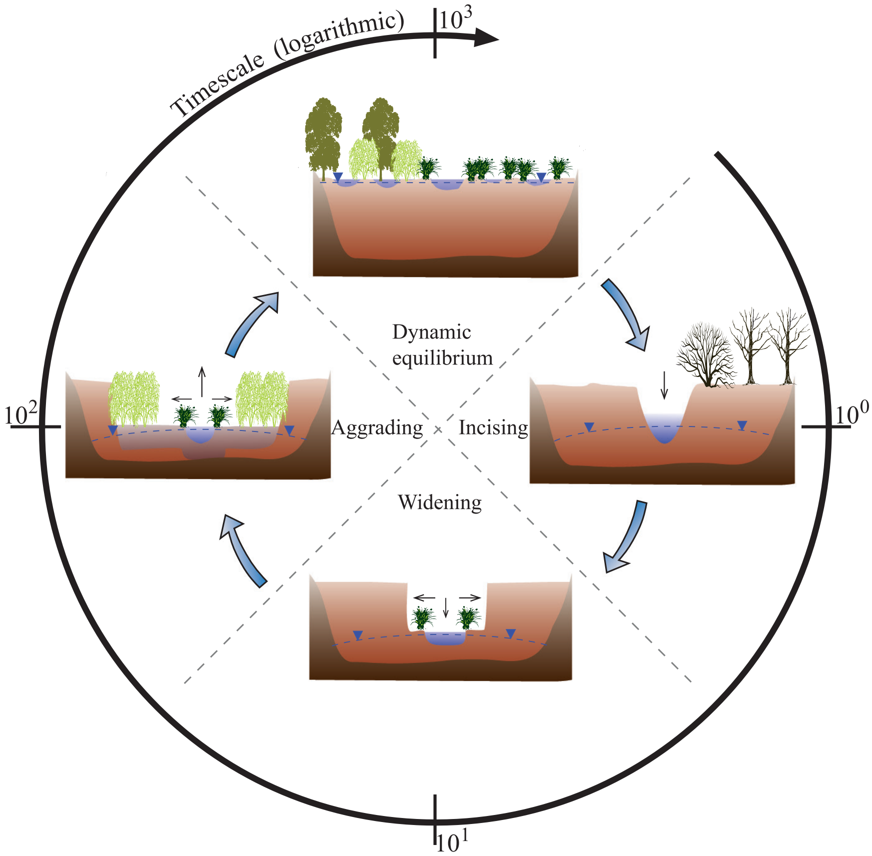

Figure 2. A simplified stream succession model showing the cyclical nature of incision-prone stream ecosystems on alluvial floodplains. Succession is divided into four phases: rapid incision, trench widening, slow aggradation, and dynamic equilibrium. This model highlights the dominant physical processes driving each phase and the common timescales for each phase. The small arrows highlight the direction of dominant and subdominant erosion or deposition; the dashed lines indicate water table elevation. Source: Adapted from Cluer and Thorne (2014).

both bed and suspended sediment loads, tipping the balance toward aggradation (Montgomery et al. 1996, Pollock et al. 2007, Green and Westbrook 2009). The slope is also reduced through backwatering upstream from the beaver dam and through effective lengthening of the stream through creation of distributary side channels (John and Klein 2004, Polvi and Wohl 2012, 2013). Although the slope is much steeper locally over the "step" of a beaver dam, the dam itself is often quite effective as an energy dissipater.

In addition, submerged floodplains upstream from beaver dams allow dense emergent vegetation to thrive, providing additional flow resistance and reinforcing long-term storage and retention of sediments through root strength (Beechie et al. 2010, Jansen and Nanson 2010, Gurnell et al. 2012). Conversely, removal of such flow obstructions should increase the potential for incision. Such practices were widespread throughout North America in the nineteenth century; beaver were trapped out, streams were cleared of large wood for splash damming and navigation, and riparian vegetation was cleared for agricultural crops or domestic livestock grazing (Cooke and Reeves 1976, Sedell and Duval 1985, Naiman et al. 1988, Collins et al. 2002, Walter and Merritts 2008).

Incision–aggradation models in the context of restoration

Restoration of an incised stream ecosystem requires understanding its present trajectory on the incision–aggradation cycle and an assessment of whether intervention should be applied to accelerate or change that trajectory. Stream incision occurs in many different climates, but the basic phases of channel incision and recovery under natural conditions are similar. However, the length of time between each phase may vary considerably (Schumm et al. 1984, Darby and Simon 1999).

For many alluvial streams that are prone to incision, there are typically four basic successional phases (figure 2): (1) rapid incision lasting from years to decades, in which sediment outputs are greater than inputs; (2) incision trench widening with continued high sediment output; (3) slow aggradation that can last for centuries or longer, in which sediment inputs are greater than outputs; and (4) dynamic equilibrium, in which the average sediment inputs and outputs are approximately equal (Elliot et al. 1999). Each phase has a number of nuanced stages (Cluer and Thorne 2014), and the time frames and complexity of the response can vary, depending on local conditions and on whether there are multiple perturbations to the system; for simplicity, we provide below a broad overview of the physical changes characterizing these four basic phases and the role of living organisms in shaping physical processes within each.

Phase 1: Rapid incision

Rapid channel incision can be initiated by a number of events: a change in stream morphology, such as straightening to improve drainage; a drop in stream base level; or removal of flow obstructions, such as beaver dams or riparian vegetation (Leopold et al. 1964, Darby and Simon 1999, Beechie et al. 2008). Once incision has begun, a single-thread channel rapidly exports sediment, continuing to remove erodible alluvium until it reaches resistant material, such as bedrock, or the channel slope adjusts to a new equilibrium (figure 2). This downcutting results in a confined, low-sinuosity stream that is more steeply sloped and disconnected from its floodplain, with flood flows concentrated within the incision trench.

Streams often incise rapidly, so that, in phase 1, there is little established vegetation on the banks or obstruction to flow, such as down wood or beaver dams. Roughness provided by the channel form itself is also reduced with the transition from a sinuous morphology of alternating pools and riffles to a simplified, linear, plane-bed morphology (Montgomery and Buffington 1997). Therefore, in phase 1, the slope and depth increase, whereas flow resistance decreases. Stream power per unit width (ω) therefore increases substantially, which results in high sediment transport capacity relative to that of the preincision phase.

Because incision depth is usually enough to lower the water table beyond the root zone of riparian vegetation, phase 1 can also result in a rapid reduction of plant biomass (Cooke and Reeves 1976). By the end of phase 1, the extent of riparian vegetation, the complexity and variation of instream habitat, and the extent and variety of off-channel habitat are each minimized (figure 2), along with the potential for a biologically diverse, productive, and structurally complex stream ecosystem (see Cluer and Thorne 2014). From an ecological perspective, the incision phase is the most degraded state of the incision–aggradation cycle and would benefit most from restorative intervention.

Phase 2: Trench widening

Under most conditions, an incised stream cannot begin to aggrade until the incision trench begins to widen and ω subsides. For streams with easily erodible banks, some widening begins with bank erosion during high flows (figure 2). This produces a local sediment supply, allowing for meander bar formation and development of a somewhat more sinuous planform. Bank erosion then accelerates on the meander bends, providing more sediment for potential aggradation downstream.

Depending on the caliber of bank materials, trench widening can propagate longitudinally. As the incision trench widens, the channel initially becomes wider and shallower, and sinuosity increases slightly such that stream power declines. Riparian vegetation typically provides relatively little flow resistance early in this phase, because channel widening is rapid and stream power is relatively high; therefore, areas suitable for colonization are limited. Beaver also have difficulty building stable dams in the initial widening phase because of high stream power and limited riparian vegetation (i.e., food and building material).

However, not all incised channels have easily erodible banks, particularly where streams are small relative to incision depth or when an erosion-resistant lithology is present (Beechie et al. 2008). In such cases, the stream channel is considered to be in a relatively stable state of arrested degradation, with sediment input and output rates approximately equal. Such a stream will remain in a stable, degraded state and is not likely to widen and ultimately aggrade unless a system perturbation increases bank erosion. We propose that many such perturbations are caused by structures of biogenic origin, including (short-lived) beaver dams, live vegetation, and the roots and boles of fallen trees that become established and ultimately die within the incision trench.

Whether it results from biogenic structures or easily erodible banks, once widening is initiated, abundant sediment is provided from local sources. As the channel meanders and erodes incision bank walls, an inset floodplain begins to form (Schumm et al. 1984). At some point, widening is sufficient for beaver to build stable dams (our observations suggest this occurs at a width of around 30–50 m), and the inset floodplain provides areas of low stream power, where dense riparian vegetation can become established.

After this point, further widening is not needed for ecosystem recovery. In fact, further widening will only increase the overall size of the incision trench and, therefore, the volume of sediment needed to refill it. Although riparian vegetation on incised banks can slow widening rates, the presence of a beaver dam is much more effective, because it reduces unit stream power and, therefore, the potential for erosion. Elevated water tables resulting from the beaver dam are also conducive to rapid expansion of riparian vegetation.

Therefore, where biogenic features are present, they largely control the extent of trench widening in a classic ecogeomorphic feedback loop (Wheaton et al. 2011). Where these features are absent, the extent of widening is controlled by erosivity of the bank walls relative to stream power, and incision trench width can be substantially greater (Simon and Rinaldi 2006). For example, arroyo systems associated with rapid fill cycles may have extensive sandy deposits, which would be much easier to erode than would a cohesive fine-grained deposit or one with a more complex depositional history (Bryan 1925, Cooke and Reeves 1976).

Trench widening can last years to decades, depending on both the hydrologic regime and the nature of bank materials (Simon et al. 2000). Widening can also be followed by another round of incision and then more widening, so that a system may cycle back and forth between widening and incision before transitioning to a phase in which aggradation is the dominant process (Schumm et al. 1984).

Phase 3: Slow aggradation

Until recently, channel-evolution models placed little emphasis on the geomorphic conditions necessary for aggradation to occur, and the conditions leading to aggradation were not well described (Darby and Simon 1999, Simon and Rinaldi 2006). According to equation 2, as a stream develops an inset floodplain and has room to meander, the stream slope decreases, which reduces stream power and thereby reduces sediment transport rates. Nevertheless, our observations suggest that, in the absence of increased flow resistance provided by living organisms or their derivatives, the

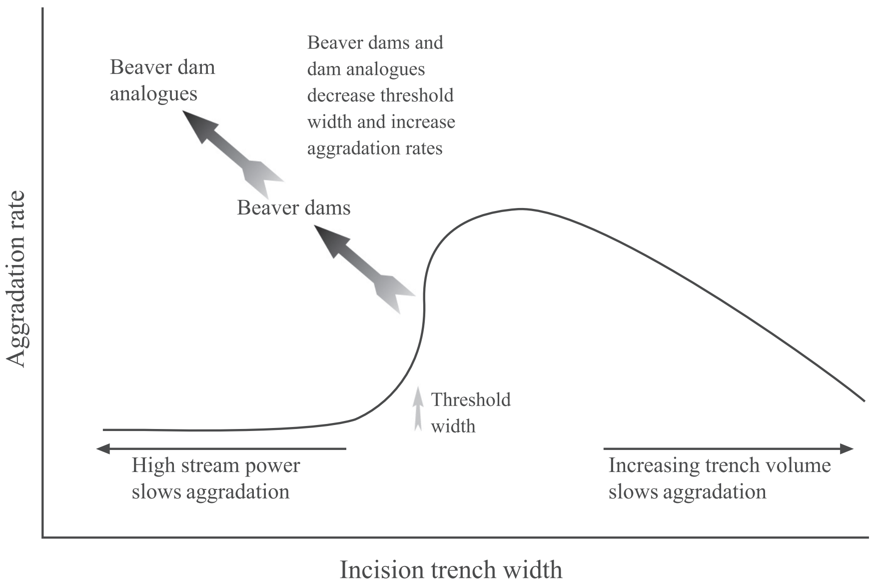

Figure 3. Incision trenches must widen to a given threshold before aggradation can occur; below this threshold, stream power is too great for sediment to be retained. Once the threshold has been reached, aggradation begins. If the incision trench continues to widen, the amount of sediment needed for the trench to rise to a given elevation also increases, lengthening the time for the stream ecosystem to recover. Therefore, there is an optimal incision trench width at which aggradation rates will be at a maximum. Because beaver dams or beaver dam analogues obstruct flow and reduce stream power, their presence can both reduce the incision width threshold and accelerate the accumulation of sediment.

incision trench will probably be slow to aggrade. We propose (a) that aggradation rates are mediated by live vegetation or dead wood and, in much of the Northern Hemisphere, by beaver dams; (b) that, in the absence of these biogenic features, aggradation will occur more slowly, if at all; and (c) that most incised alluvial streams are largely dependent on biogenic flow obstructions to transition to a phase-3 condition.

Even in the presence of biogenic flow obstructions, aggradation can proceed quite slowly relative to incision and widening (figure 2). Although incision and trench widening generally occur over years to decades, aggradation may occur much more slowly. It may take a century or more (Elliot et al. 1999) for the stream to return to a bed elevation close to its preincision condition, with the rate of aggregation determined primarily by the rate of sediment input from upstream sources (Pollock et al. 2007).

As aggradation occurs, ecosystem functionality also increases (see Cluer and Thorne 2014), particularly in the maintenance of biodiversity, which is affected by water table levels (Pollock et al. 1998). As formerly incised or gullied reaches recover upstream, sediment supplies will decrease. At some point in the recovery process, sediment inputs and outputs will be approximately equal, and the system will reach dynamic equilibrium.

Phase 4: Dynamic equilibrium

Equilibrium conditions in an incision-prone stream can manifest themselves in different ways, depending primarily on climate, the stream slope, and peak flow discharge. An equilibrium stream may take the form of a classic single-thread channel but may, alternatively, have no stream channel or evidence of surface flow other than a broad, vegetated swale (Zierholz et al. 2001). This would be the equilibrium endpoint, for example, of an open channel formed by gullying.

Another ecologically valuable form of equilibrium is the heavily vegetated, multithread channel with slow-moving water, relatively undefined banks, and no clear transition between the channel's edges and riparian vegetation (Walter and Merritts 2008, Burchsted et al. 2010, Jansen and Nanson 2010). Such streams have multiple obstructions formed by large down wood, snags, live trees, dense vegetation, and beaver dams. These obstructions can be so extensive that at least some large river valley bottoms were described more as large, frequently flooded swamps than as a river next to an occasionally inundated floodplain (Sedell and Froggatt 1984). Available evidence suggests that such streams have high ecological functionality and were once common throughout much of the world (Collins et al. 2002, Polvi and Wohl 2012, 2013).

Using beaver dams to restore incised streams

Under natural conditions, beaver and riparian vegetation are integral components of many alluvial stream ecosystems (Naiman et al. 1988, Pollock et al. 2003, Burchsted et al. 2010). Therefore, to a large extent, accelerating the recovery of incised streams involves the removal of the stressors that preclude the establishment of these components (e.g., riparian grazing or active beaver trapping). However, identifying these stressors may require a basic understanding of ecosystem dynamics and food-web interactions. For example, in Yellowstone National Park, the recovery of beaver populations was facilitated by the reintroduction of wolves. Marshall and colleagues (2013) proposed that wolf reintroduction changed behavior patterns in elk, such that elk avoided predation by spending less time browsing riparian areas. This may have allowed for the expansion of woody riparian species such as willow and cottonwood, providing sufficient food and dam-building materials for beaver populations to expand (Ripple and Beschta 2004).

The establishment of natural beaver dams in an incised stream is likely to be most successful and beneficial about

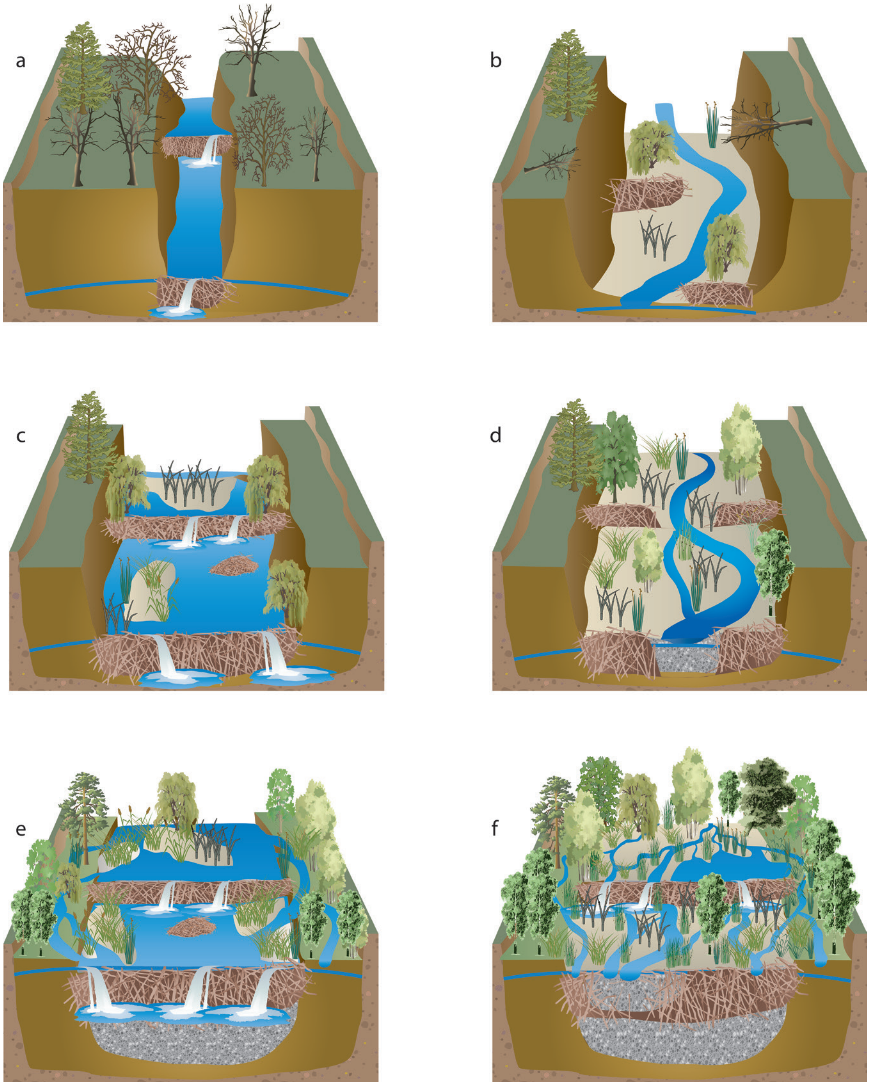

Figure 4. How beaver dams affect the development of incised streams: (a) Beaver will dam streams within narrow incision trenches during low flows, but stream power is often too high, which results in blowouts or end cuts that (b) help widen the incision trench, which allows an inset floodplain to form. (c) The widened incision trench results in lower stream power, which enables beaver to build wider, more stable dams. (d) Because streams that have recently incised often have high sediment loads, the beaver ponds rapidly fill up with sediment and are temporarily abandoned, but the accumulated sediment provides good establishment sites for riparian vegetation. This process repeats itself until (e) the beaver dams raise the water table sufficiently to reconnect the stream to its former floodplain. Eventually, (f) vegetation and sediment fill the ponds, and the stream ecosystem develops a high level of complexity as beaver dams, live vegetation, and dead wood slow the flow of water and raise groundwater levels such that multithread channels are formed, often connected to off-channel wetlands such that the entire valley bottom is saturated (Sedell and Frogatt 1984, Walter and Merritts 2008).

midway through phase 2 (trench widening). During phase 1 and early in phase 2, the incision trench is too narrow and stream power too high for dams to persist, although they may deflect flow against the banks, causing erosion and accelerating widening of the incision trench (Demmer and Beschta 2008). As the incision trench widens and an inset floodplain forms, stream power decreases, and the potential for beaver dams to remain intact increases. Although the widened incision trench increases the likelihood of a stable dam, in terms of vertical aggradation, the optimal incision trench width is the minimum width at which stable structures can be maintained (figure 3).

Figure 4 illustrates the likely influence of beaver dams on the successional trajectory of an incised stream. Initially, the dams are built in trenches that are too narrow, and they fail repeatedly. But even as they fail, these dams deflect flow against the banks and help accelerate widening. This process continues until the trench is wide enough to sustain dams and aggradation can occur. Of course, beaver build dams to create ponds, not to aggrade incised streams, and when ponds fill with sediment, the dams are abandoned. Nonetheless, the dam-building process begins to create a more structurally complex and dynamic stream ecosystem. In particular, the bed deposits above abandoned beaver dams can be quite heterogeneous: They are frequently interspersed with both fine and coarse sediments (from fluctuating water levels and velocities), as well as wood (from food caches) and organic material (Rudemann and Schoonmaker 1938, Rutten 1967, Polvi and Wohl 2012). Such deposits are more resistant to future incision.

Abandoned dams are frequently breached, and some of the sediment behind them is subsequently transported, but it is rare for the entire deposit to be excavated (e.g., Walter and Merritts 2008). Where vegetation can become established on the aggrading surface, roots help bind the substrate, and the aboveground components can lower flow velocities. This helps reduce reincision of aggraded material from behind the dam and enables floodplain aggradation to continue (Pollock et al. 2007, Jansen and Nanson 2010, Gurnell et al. 2012). The cycle of beaver dam construction and rapid aggradation, followed by dam abandonment and slower, vegetation-mediated aggradation, repeats itself at different rates and in different locations within the incised channel.

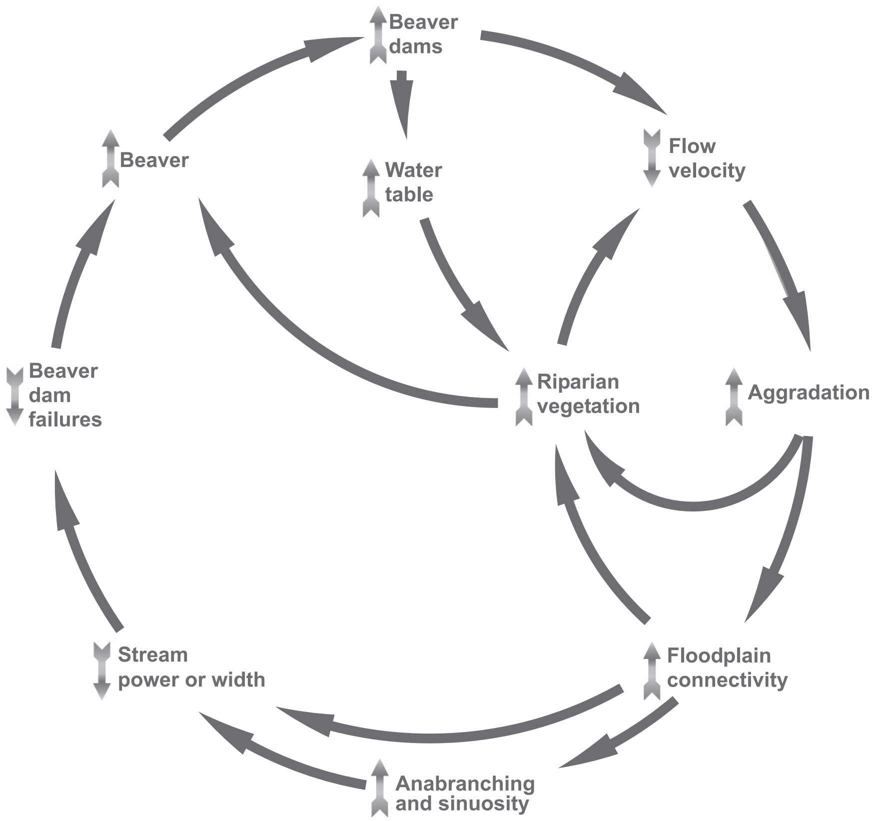

Figure 5. Beaver build dams in incised stream trenches that create positive feedback loops that alter physical processes in streams and change vegetation dynamics such that they ultimately improve habitat for the beaver themselves, which makes it possible for them to sustain colonies and expand their populations.

resistance and reduced bank erosion, helping to change a wide, shallow channel into a narrow, deep one. Subsequently, beaver recolonized the stream, which greatly increased the biomass of riparian vegetation, improving habitat for a number of native fishes and generally increasing the structural complexity of the system. Although these changes greatly reduced stream power, the trench is so wide that raising the streambed to its preincision level will probably take centuries or longer (figure 6).

For a stream in this (figure 6c) condition, primary functional losses are related to a lowered water table and reduced groundwater storage. Nonetheless, this phase-3 system provides numerous important ecological functions similar to those found in a phase-4 stream. Dynamic equilibrium for this system could be a highly anastomosed stream winding its way through an emergent wetland dense with vegetation and beaver dams, with little evidence of a clearly defined channel. Alternatively, if the system continues to aggrade, surface flow may disappear altogether, and the channel will be entirely replaced by a broad, vegetated swale with most flow occurring beneath the surface (see figure 2).

This cycle also leads to an overall increase in habitat heterogeneity and structural complexity of the stream ecosystem (John and Klein 2004, Burchsted et al. 2010, Polvi and Wohl 2012). The rate of aggradation is controlled primarily by the availability of sediment and beaver population growth rates. Beaver population growth is, in part, controlled by food availability, which is, in turn, affected by beaver dams. Therefore, once they are established, beaver tend to create a positive feedback loop that improves their own food supply, enabling more dams to be constructed (figure 5) and further increasing food availability (Donkor and Fryxell 1999). Access to a larger and more complex riparian and wetland foraging area is also likely to enhance beaver survival by reducing predation risk.

During late phase 2 or phase 3, introduced beaver can provide great benefit to incised stream ecosystems, but the rate of return to phase 4 will necessarily be slower because of the larger volume of sediment needed to refill the trench. As an example, figure 6 illustrates the 20-year recovery sequence of a phase-3 stream in Nevada, where ecosystem functions were substantially restored simply by reducing the intensity of livestock grazing. The removal of this stressor allowed natural riparian vegetation to recover, which increased flow

Using BDAs to restore incised streams

Recovery to a dynamic equilibrium phase will be more rapid when trench widening is minimized, because the volume of sediment needed to fill the excavated incision trench is lower. Mitigating against restoration during rapid incision is a high bed load transport rate and little opportunity for the retention of fine sediments on the inset floodplain. Under such conditions, few natural structures are likely to develop at concentrations sufficient to cause aggradation. However, human-engineered analogues of natural structures can be placed in narrow incision trenches, and these are often sufficient to increase flow resistance and initiate aggradation. Such analogues include channel-spanning logjams, boulder steps, and BDAs (Shields et al. 1994, Pollock et al. 2012). Analogues can also be designed to create hydraulic irregularities or concentrate flow sufficiently to erode resistant banks, widen the incision trench, and enhance the sediment supply for downstream reaches.

Figure 7 shows a hypothetical recovery sequence of an aggraded stream using BDAs. In figure 7a, stream power is too high for engineered obstructions to retain sediment, so the incision trench is widened by deflecting flow onto banks. This induces erosion and widening, which accelerates the

Figure 6. Recovery sequence of an incised stream ecosystem over a 20-year period. In 1993, (a) the stream was open to annual summer grazing by cattle. After 1999, (b) grazing was limited to cow–calf pairs during spring and fall. By 2012, (c) beaver had established a persistent colony for several years. The size of riparian vegetation had substantially increased, and vegetation now extended across the entire width of the incision trench, because beaver dams had elevated the water table. Upstream of the dams, the channel is (for now) wide and deep. Dams and the density of riparian vegetation further increase flow resistance and reduce stream power, creating conditions ideal for the retention of sediment, but the trench width will make aggradation rates low. Photographs: Carol Evans, Bureau of Land Management.

transition to phase 2 (figure 7b). This is followed by placement of BDAs intended to cause aggradation (figure 7c, 7d). Ultimately, the upstream pool formed by the BDA fills in (figure 7e), raising the streambed level. Subsequently, another series of structures is placed on the aggraded bed, and the process is repeated until the desired elevation is reached (figure 7f).

Engineered flow obstructions have some potential advantages over natural structures. They can be designed for a specific outcome (e.g., aggradation or trench widening) and to withstand the flow forces that they are likely to encounter. Their placement can also be better controlled, and they can be adjusted as needed to facilitate restoration objectives. However, control of the system as a whole will be limited.

Like natural beaver dams, BDAs are temporary features on the landscape. The BDA is intended to invoke a process response, not to remain as a permanent hard structure. Similar to the multiple dams found in beaver colonies, the placement of multiple BDAs is critical. Multiple placements will increase the overall system resilience and downplay its dependence on the structural integrity of any individual structure. Like natural beaver dams, when a BDA is breached, it often produces more heterogeneous habitat (see Demmer and Beschta 2008).

Although this recovery pathway is initiated by active restoration, its success ultimately depends on colonization by vegetation and beaver. That is, although artificial structures can cause rapid aggradation, vegetation is still needed to increase flow resistance on banks and aggraded surfaces, and beaver may be needed to maintain and expand on BDAs. The key to success in the use of BDAs is ensuring that they are maintained and repaired as needed until the streambed has reached the elevation of a wide terrace or former floodplain, as is illustrated in figure 4f. The identification and elimination of the stressors that caused the incision in the first place are also critical (Schumm et al. 1984).

Applicability of the restoration approach

The applicability of this restoration approach is largely confined to incised streams where beaver can or could build dams. This includes small to midsize low-gradient, unconfined streams in North America, north of the Mexican border, and much of the temperate regions of the Eurasian continent. The range of physical conditions under which beaver can build dams has been described elsewhere, using a variety of measures, such as the stream slope, stream power, and valley width (e.g., Retzer et al. 1956, Suzuki and McComb 1998, Pollock et al. 2003, 2004, Green and Westbrook 2009). Generally, perennial streams with a slope of less than 6%, an unconfined valley or incision trench (valley width ÷ channel width > 4), and a bankfull stream power of less than 2000 watts per m are physically favorable for beaver dams. However, beaver also build seasonal dams on streams with much greater stream power. Such dams are often breached during winter floods but are then rebuilt once flows have subsided. Such dams can last multiple years

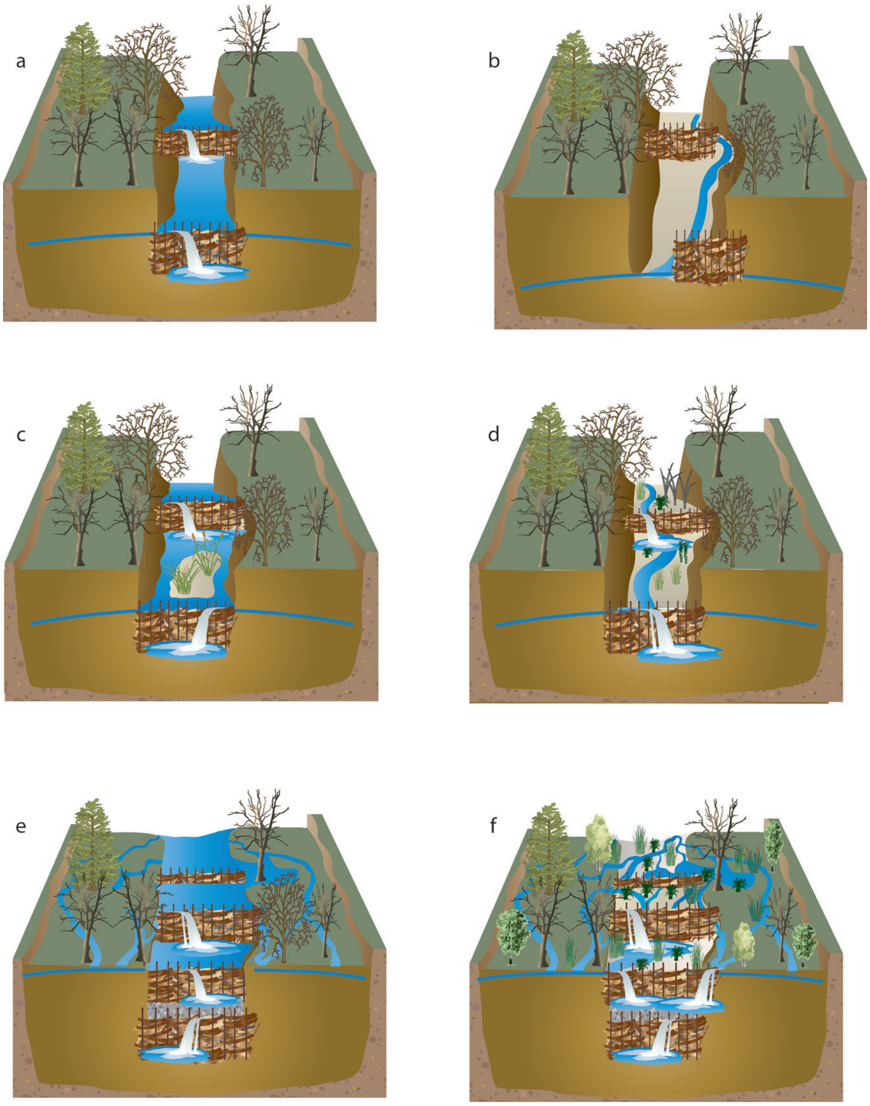

Figure 7. Sequence of observed stream ecosystem changes when beaver dam analogues (BDAs) are used to aggrade a stream. BDAs mimic many functions of beaver dams but can be placed where they will most benefit streambed aggradation and at higher densities than those typical of natural beaver dams. Their key advantage over beaver dams is that they are structurally sound enough to be used in narrow incision trenches and have less potential for failure once ponds are formed. This can substantially lower the time required for floodplain reconnection, because the volume of fill needed is lower in narrower trenches. Where sediment supplies are abundant, high BDA densities can rapidly reconnect streams to their former floodplains.

if no major flooding occurs. Beaver have also been observed building dams on more steeply sloping streams (up to 16%), but this is less common, and they have also been observed to convert intermittent streams into perennial streams (Pollock et al. 2003). The use of BDAs may somewhat expand the range of physical conditions under which this restoration approach is suitable, but, generally, BDAs will lengthen the duration of dams rather than expand the physical conditions under which dams can occur.

For larger streams, more-confined streams, streams with greater stream power, or streams on steeper slopes, other techniques can be used to achieve similar objectives. In particular, the use of channel-spanning logs and channel-spanning logjams can be used in many locations that are unsuitable for beaver or BDAs (see Wohl 2011, Polvi and Wohl 2013 for extended discussions), and properly designed channel-spanning boulder weirs are another option for achieving many of the restoration objectives that we have described.

At the watershed scale, assessing restoration potential requires the evaluation of both sediment supply and the potential for retention and aggradation in various reaches. Sediment supply can be quantified using a sediment budget for the watershed upstream of the reach or by measuring sediment discharge near the reach. For example, Mapes (1969) created a sediment budget and showed that suspended sediment constituted more than 90% of the total sediment load for two river basins in eastern Washington State. Beechie and colleagues (2008) adapted these data, along with measured incision volumes and aggradation rates from multiple literature sources, to evaluate restoration potential for incised channels within the same basins. Their analysis showed that more than enough sediment was available to achieve aggradation rates of 0.03–0.10 m per year but that a modest introduction of beaver could reduce the time needed for stream reaches to reconnect with the historical floodplain from 60–270 years to 40–186 years (Beechie et al. 2008). Such watershed-scale geomorphic analyses are an essential step in assessing both sediment supplies and geomorphic conditions within an incised stream network. The tools available for these analyses also include the fluvial audit method of Sear and colleagues (2009) and the river styles approach of Brierley and Fryirs (2005).

The depth and width of the incision trench also influence the feasibility of recovery: Deeper and wider trenches require more sediment to fill channels to the point of reconnection with the historical floodplain. Incised channels that are shallower and narrower will take less time to fill and are therefore more feasible to restore. The depth to the water table and potential vegetation recovery on either the inset floodplain or the historical floodplain are important considerations when incision has lowered the water table to levels that riparian plants cannot reach. For example, to restore incised reaches on Bridge Creek, Oregon, Pollock and colleagues (2012) are using beaver and BDAs. In selecting appropriate reaches for restoration, they identified those with wide, inset floodplains less than 1 m above the water table (Pollock et al. 2012). At this elevation, raising the water table only 0.5–0.7 m can allow riparian vegetation to establish on the inset floodplain surface.

Conclusions

Stream incision is a widespread problem that substantially degrades aquatic and riparian habitats. Incised stream ecosystems can recover naturally, but the process may take centuries. At present, models describing the recovery of incised streams are focused primarily on physical processes. We have presented an ecology-based stream-succession model that includes both physical and biological processes. Specifically, we propose that incised streams begin to aggrade when stream power is reduced below a critical threshold and that the interaction of living organisms with physical processes is essential to reducing stream power and, more generally, to facilitating stream ecosystem recovery.

Beaver dams and riparian vegetation create flow obstructions that reduce stream power and flow velocity. These reductions, in turn, allow sediment to accumulate on the streambed and floodplain while also reducing bank erosion. Restoration strategies that incorporate how features such as beaver dams, live vegetation, and dead wood interact dynamically with fluvial geomorphic processes are more likely to be successful. An assessment of where a stream lies in the incision–aggradation cycle is essential to developing a successful restoration strategy. Sufficient restoration may consist of simply removing the external stressors that preclude the establishment of riparian vegetation and beaver colonies. However, in many cases, construction of BDAs or similar structures can substantially accelerate the recovery of incised streams.

Acknowledgments

The authors are grateful to Brian Cluer and Ellen Wohl, two forward-thinking scientists who helped inspire the ideas developed in this Overview. Ian Tattam also provided excellent commentary and lively feedback over the course of many field expeditions to examine degraded streams and beaver ponds. We are thankful to Carol Evans of the Bureau of Land Management, who has been actively using beaver to restore incised streams and who provided the photographs used in figure 6 of this article. George Pess, Phil Roni, and Peter Kiffney provided internal Northwest Fisheries Science Center (NWFSC) peer reviews of the manuscript, and three anonymous reviewers provided additional peer review, all of which helped improve the quality of this work. Funding for this project was provided by internal NOAA (National Oceanic and Atmospheric Administration) and NWFSC funds, and the Bonneville Power Administration provided funding for a related field study that was essential in the development of the concepts put forth in this article.

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