Geomorphic evolution of restored montane meadows: twenty years of 'Pond and Plug' restoration of incised channels, Sierra Nevada of California

L'évolution géo-morphique des prairies alpestres restaurées : Vingt ans d'utilisation de la technique « Pond and Plug » pour restaurer les canaux incisés dans les vallées de la Sierra Nevada de Californie

Jennifer Natali, Matt Kondolf

University of California, Berkeley. jennifer.natali@berkeley.edu

RÉSUMÉ

Les organismes de conservation qualifient la moitié des quelque 17 000 prairies de la Sierra Nevada en Californie d'écosystèmes dégradés en raison de l'incision des chenaux qui draine les aquifères peu profonds et déplace les communautés végétales dépendant des eaux souterraines. L'approche « Pond and Plug » pour la restauration des prairies, inaugurée en 1996, consiste à boucher (ou fermer par des barrages) des canaux alluviaux profonds avec des sédiments prélevés dans la prairie, créant ainsi des bassins qui en sont un sous-produit. Le succès de la restauration à court terme, démontré par l'élévation du niveau des eaux souterraines et le retour de la végétation hydrophyte, a conduit à l'adoption de la technique « Pond and Plug » dans la plupart des restaurations de prairies de la Sierra Nevada. Cette étude documente l'évolution sur 20 ans de la morphologie des chenaux dans huit des plus anciens projets de restauration de prairies en « Pond and Plug » et passe en revue les approches employées pour la planification et la conception, les relevés répétés des transects de surveillance et les profils longs des chenaux ainsi que l'analyse du processus géo-morphique aux échelles des chenaux, des prairies et des bassins. Les résultats montrent que les niveaux d'eau souterraine continuent d'entretenir la végétation des prairies humides, mais les avulsions des chenaux, les coupes et l'érosion soulèvent des questions quant à la viabilité à long terme des morphologies des chenaux peu profonds qui maintiennent les nappes phréatiques proches de la surface. Compte tenu des observations sur l'instabilité des chenaux, les appels à l'adoption généralisée de la technique devraient être tempérés par la recherche et la surveillance pour combler les lacunes et remédier à l'incertitude des connaissances.

ABSTRACT

Conservation organizations classify half of the ~17,000 meadows in California's Sierra Nevada as degraded ecosystems due to channel incision that drains shallow aquifers and shifts groundwater-dependent vegetation communities. The 'Pond and Plug' approach to meadow restoration, pioneered in 1996, plugs (or dams) incised alluvial channels with sediment dug onsite from the meadow, creating ponds as a byproduct. Short-term restoration success, as demonstrated by raised groundwater levels and return of hydrophytic vegetation, led to adoption of 'Pond and Plug' as a predominant meadow restoration technique in the Sierra Nevada. This study documents the twenty-year evolution of channel morphology in eight of the earliest 'Pond and Plug' meadow restoration projects through a review of planning and design approaches, repeat surveys of monitoring transects and meadow channel long profiles along with analysis of geomorphic process at the channel, meadow and basin scales. Results show that groundwater levels continue to support wet meadow vegetation, but channel avulsions, headcuts, and erosion raise questions regarding the long-term viability of shallow channel morphologies that maintain near-surface water tables. Given observations of channel instability, calls for widespread adoption of the technique should be tempered with research and monitoring to address knowledge gaps and uncertainty.

KEYWORDS

Restoration, incision, meadow, channel morphodynamics, groundwater

1 INTRODUCTION

1.1 Incised Channels and Degraded Meadows of the Sierra Nevada

Within low-slope alluvial valleys of California's Sierra Nevada Range, over 17,000 montane meadows support groundwater-dependent ecosystems but encompass just 1% of the forest-dominated area. Shallow aquifers within valley alluvium support highly-valued "hot spots" of terrestrial and aquatic primary productivity fed by seasonal snowmelt in a water-limited climate of summer droughts (Viers et al. 2013). Conceptual models of idealized meadows assume that the region's meadows should support single-thread meandering channels that have reached an equilibrium state since the last glacial maximum with stability conferred by predictable, seasonal snowmelt and dense vegetation.

Conservation organizations classify half of Sierran meadows as degraded ecosystems due to channel incision that drains shallow aquifers. Without near-surface groundwater (~1 m depth), meadow vegetation communities shift from hydrophytic graminoids to drought-tolerant grass or sagebrush species or succumb to pine forest invasion. Sources blame past anthropogenic disturbance as the cause of channel incision with first reports occurring around 1900 after a period of intensive grazing in the region, but coinciding with other changes in land use, fire suppression and climate. Subsequent to incision, channel widening continues to yield fine sediment that buries downstream aquatic habitat and contributes to reservoir sedimentation. Drained shallow aquifers across degraded meadows in the region represent lost groundwater storage capacity. Restoration objectives most often focus on reducing downstream sedimentation and raising groundwater levels. Based on models that link increased channel depth to lowered groundwater levels, restoration approaches assume that objectives will be realized and sustained by re-introducing a stable, shallow channel morphology that supports frequent overbank flows (e.g. 2-year recurrence interval) and a protective 'armor' of dense floodplain vegetation to resist erosive forces of flows.

1.2 Pond and Plug Restoration in Montane Meadows

Early attempts to restore incised channels through bio-engineering (i.e. brush dams, increased roughness) or hardened checkdams (i.e. rock, concrete) often faced re-incision over time. A new meadow restoration approach, deemed 'Pond and Plug', was pioneered in 1996 as a method to plug (or dam) incised channels with sediments dug onsite from the meadow, creating ponds (or voids of sediment that fill with groundwater) as a byproduct. Restoration designs divert flow away from the former channel, either into relict channels, engineered channels or onto meadow floodplains. Early monitoring of initial projects documented a near-immediate rise in groundwater levels and a return of desired hydrophytic graminoid vegetation, such as sedge and rush. This success led to adoption of 'Pond and Plug' as a predominant restoration method in degraded Sierran meadows. Conservation organizations and government agencies call for further adoption and investment in 'Pond and Plug' to support regional ecosystem restoration, climate adaptation and carbon sequestration goals.

1.3 Post-Project Appraisal

This study documents the twenty-year evolution of channel morphology in eight of the earliest 'Pond and Plug' meadow restoration projects through a review of planning and design approaches, repeat surveys of monitoring transects and meadow channel long profiles, and analysis of geomorphic context, processes and conceptual models of meadow evolution. This post-project appraisal of one restoration technique implemented across a single region supports adaptive management of montane meadows (Downs and Kondolf, 2002) as forest managers and conservation groups seek to reverse declines in populations of endangered species and mitigate threats of climate change, but often focus on funding and implementing individual projects.

2 METHODS

2.1 Sites

We selected eight restored meadow sites from a comprehensive list of all Pond and Plug meadow restoration sites across the Sierra Nevada but narrowed to the oldest projects (> five years since restoration) that had project planning and design documentation along with monumented topographic channel cross sections that recorded constructed channel geometry.

Figure 1. Location of eight meadow study sites within the Sierra Nevada Range of California, USA

2.2 Field Survey and Data Analysis

Using a total station, we re-surveyed monumented channel cross sections and long profile to determine stream gradient, pool and riffle spacing, variance of bed elevation, and patterns of deposition and erosion along the restored channel from the upper to lower meadow boundary. At each cross section, we documented channel bed grain size distribution, bank stratigraphy, and bank vegetation height along with a map of facies for the reach. For three valley-width transects per meadow, we surveyed and calculated percent cover of broad vegetation types which informed aerial imagery analysis of vegetation cover. Coupled with aerial imagery analysis of channel form, surveys allowed calculation of channel characteristic metrics such as bed slope, width-to-depth ratios, geometric mean of grain size distribution, planform meander wavelength and sinuosity, bed and bank shear stress as well as comparison of pre- and post-restoration incision. By comparing 2014-15 topographic survey results with constructed channel geometry, we estimated volumes of channel erosion versus deposition over time.

3 RESULTS AND DISCUSSION

3.1 Observations

Surveys show that groundwater levels continue to support wet meadow vegetation, but some channels have avulsed and reconnected to former flowpaths through constructed plugs. In these cases, headcuts emanate upstream of ponds. Banks erode and channels widen through reaches where floodplain alluvium includes sand layers that lack cohesion. Deepened scour of outer banks has punctuated placed gravels and increased local slopes. Placed gravels at armored riffles have washed away. In some designs, ponds capture eroded sediment demonstrating the potential for restored meadows to redistribute alluvial material and sustain shallow and meandering channel morphologies but ponds also introduce deep stillwater, disrupt sediment connectivity, and create novel habitat. Beavers now occupy restored meadows with perennial flows, offering mixed effects across projects. In some cases, beaver dams maintain plug stability by resisting flows, but they also introduce novel habitat dynamics with backwaters, avulsions and sudden release of sediment as dams break. In some cases, changes to channel morphology reflect expected dynamics of meandering channels (i.e. lateral migration of outer bends with inner bend bar construction), but in others, the shifts point to weaknesses in pre-project monitoring and diagnoses, channel engineering practices, and our understanding of multi-scale processes that influence sediment deposition and scour across a channelized alluvial valley.

3.2 Discussion

Although a few projects used one-dimensional hydraulic models to understand stability of channel designs, fundamental factors that influence alluvial channel stability such as incoming sediment supply, existing floodplain deposits or base level control remain unrecognized influences on erosive and depositional forces acting on meadow floodplains. At the meadow head, post-restoration avulsion and relict distributary channel patterns signal that as channel slopes transition from confined canyons to widened meadow floodplains, sediment deposition fans across the meadow with a tendency toward unstable channel form. This avulsion process likely builds the meadow floodplain over time. At the meadow outlet, the form and stability of base level control often depend on depositional patterns of past climatic eras (e.g. terminal moraines or side-valley fans deposits). By considering the geomorphic processes that build and sustain meadow floodplains through the interglacial period, some meadow restoration investments could be deemed unjustified impositions because channel incision through unstable deposits (i.e. toe of fans, layers of sand) represent an expected evolution as flows rework competing sediment inputs. Perhaps not all meadow stream channel incision is due to a past anthropogenic and non-recurring disturbance – in many cases, evidence for this remains anecdotal.

Project planning and design could be better informed by analyses of existing floodplain deposits, characteristics of incoming sediment input, and improved diagnoses of the causes of incision in terms of their spatial scale and time period of operation. While the Pond and Plug approach promises to mitigate effects of climate change by increasing groundwater storage capacity in Sierran headwaters, conceptual models and restoration designs do not recognize how climate change may impact the interacting factors that confer meadow stability.

4 CONCLUSION

Given the uncertain stability of restored meadow channels, calls for widespread adoption of the Pond and Plug technique should be tempered with research and monitoring to address knowledge gaps. As the latest iteration of approaches to damming incised channels, ‘Pond and Plug’ introduces novel features and processes into meadow floodplains and addresses interaction between the channel depth and groundwater, but not geomorphic processes that sustain shallow channel morphologies through a shifting climate in a montane region with forestry- and tourism-based land use.

Californians prize meadows of the Sierra for their beauty, their ability to hold water through dry summers and support highly productive ecosystems. Rather than applying Pond and Plug broadly across all degraded meadows, we should pause to ask where restoration investments will be most worthwhile, where meadows can be allowed to heal themselves, versus where incision may be an expected natural process. Where a known anthropogenic disturbance acts directly on the meadow, restoration may be more appropriate than where unknown causes may continue to alter flow and sediment regimes outside their historical range of variability. Developing and testing a model of factors that confer meadow stability through changing climates could support more targeted, strategic regional planning for meadow restoration. Such analysis may help incorporate approaches to restoration that operate on a watershed-scale such as changes to wildfire management, road and trail infrastructure, grazing practices or land use.

LIST OF REFERENCES

Downs, P.W. and Kondolf, G.M. (2002). Post-project appraisals in adaptive management of river channel restoration. *Environmental Management, 29(4), 477-496.*

Viers, J.H., Purdy, S.E., Peek, R.A., Fryjoff-Hung, A., Santos, N., Katz, J., Emmons, J., Dolan, D., and Yarnell, S.M. (2013). *Montane meadows in the Sierra Nevada: changing hydroclimatic conditions and concepts for vulnerability assessment.* Center for Watershed Sciences Technical Report, U.C. Davis. 67 pp.