ANNOTATED BIBLIOGRAPY OF SELECTED PUBLICATIONS RELATED TO HYDROLOGIC EFFECTS OF WET MEADOW RESTORATION IN THE SIERRA NEVADA

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Introduction

Meadow restoration has many potential benefits, including improved water quality, streamflow regimen, flood attenuation, aquatic and terrestrial habitats, aesthetics, and forage production, and reduction of forest fuels. Although most of these benefits enjoy wide public support, the effects of restoration on downstream surface flows remain controversial owing to the temporary retention and increased evapotranspiration of water in restored meadow aquifers.

Restoration of eroded wet meadows in the Sierra Nevada is a goal of the USDA Forest Service Pacific Southwest Region. The National Environmental Policy Act requires that the "best available science" be used to assess potential effects of proposed restoration projects on National Forests. This bibliography summarizes selected references that may be useful for analyzing the effects of proposed meadow restoration projects on downstream baseflows. It is intended to aid National Forest hydrologists on interdisciplinary teams charged with analyzing effects of alternative approaches to meadow restoration, and to provide background information for our ongoing meadow hydrology assessment in the Sierra Nevada.

This bibliography is divided into 11 major topics (A to K). Each major topic has a short introductory paragraph. Titles within each topic are listed alphabetically by author and numbered sequentially for ease of reference. For each publication, I have provided a web link and a brief summary of results relevant to effects of restoration on streamflow. Publications are listed under only a single major topic, but may have relevance for others as well. The topics most likely to be useful for meadow restoration NEPA are A through F, which are specific to mountain meadows in the western United States. Topics G through K deal with groundwater-surface water interactions from other geographic areas, and are primarily intended as supporting information for our ongoing meadow hydrology assessment.

This bibliography focuses on the issue of summer baseflows downstream of restored meadows. Although some of the references deal with related topics such as vegetation response and flood attenuation, I did not attempt to collect all, or even most, of the literature on these topics, or others such as the origins and chronology of meadows, causes of meadow erosion, effects of livestock grazing, or technical standards for restoration. If you would like additional information on these or other related topics, please contact me.

The available literature on most of the main topics is much more extensive than the studies summarized below. Topic A. is an exception—I have cited all published information I could find that is directly relevant to this topic.

A. Meadow restoration effects on groundwater storage and streamflow in the western United States

Most studies have demonstrated that restoration increases summer baseflows downstream of restored meadows. The studies have been primarily undertaken in the northern Sierra Nevada on large and relatively low-gradient meadows along tributaries of the Feather River.

- Cornwell and Brown (2008). Plug and pond meadow restoration increased groundwater storage. Effects on streamflow were not evaluated.

- Elmore and Beschta (2006). Provides a general discussion of adverse impacts of stream incision on summer baseflows in eastern Oregon rangelands and provides photographic and anecdotal information on improved baseflow volumes and duration for streams restored to aggrading conditions using grazing strategies and vegetative manipulation.

- Hammersmark, Rains, and Mount (2008). Plug and pond meadow restoration in Lassen County resulted in higher water table elevations, increased groundwater storage, a non-detectable decrease in total annual streamflow, and a decreased duration of base flow at the midpoint of the restored meadow reach. Baseflow downstream of the restored reach was reported to have increased after restoration, but was not quantified. The decreased mid-meadow baseflow was attributed to increased evapotranspiration and increased downstream groundwater discharge that was not included as streamflow.

- Heede (1979). Restoration of a watershed in western Colorado using range management and check-dam construction in gullies eroded in alluvial valley floors restored perennial flow to streams within 7 years after restoration.

- Klein, Clayton, Alldredge, and Goodwin (2007). Evaluation of restoration of a large meadow in Idaho showed that restoration resulted in increased duration, extent, and volume of overbank flooding.

- Liang et al. (2007). Plug and pond restoration in Last Chance Meadow along a tributary of the Feather River in Plumas County was shown with a modeling approach to increase summer baseflows.

- Loheide and Gorelick (2006). Water temperature data were used to infer increased baseflow in restored meadow reaches relative to unrestored reaches in the upper Feather River watershed (Plumas NF).

- Loheide and Gorelick (2007). Meadow restoration along tributaries to the Feather River increases groundwater residence time and may contribute to late summer streamflow duration owing to longer groundwater flow paths relative to incised meadows.

- Loheide and Booth (2010). Effects of channel incision and widening on vegetation and groundwater in alluvial aquifers such as meadows were evaluated. Effects on streamflow were not analyzed.

- Ponce and Lindquist (1990). Provides examples of several western mountain meadows where restoration, primarily with check dams, converted ephemeral channels to perennial flow.

- Swanson, Franzen, and Manning (1987). Meadow restoration with check dams in northwestern Nevada transformed about a mile of intermittent channel to perennial flow.

- Ramstead, Allen, and Springer (2012). This review article surveyed available published and grey literature to evaluate evidence for effectiveness of meadow restoration projects in the Southwestern U.S. (including projects in the Sierra Nevada). The authors noted that few studies have produced adequate long-term data to determine hydrologic effects of restoration, but that most results to date were positive in terms of groundwater levels and baseflow.

- Tague, Valentine, and Kotchen (2008). Plug and pond restoration of Trout Creek near Lake Tahoe resulted in higher water-table elevations and increased mid-summer streamflow. Post-restoration streamflow in late summer was about the same as pre-restoration flow.

B. Erosion and restoration effects on meadow vegetation in the western United States

This topic is not directly relevant to restoration effects on streamflow, but may be helpful for NEPA analyses of post-restoration vegetation, including no-action alternatives.

- Allen-Diaz (1991). Plant species composition on meadows at Sagehen Creek (Tahoe NF) were largely controlled by depth to the water table.

- W. P. Cottam (1929). Historical observations were used to illustrate relations between human land disturbance, meadow erosion, and subsequent shifts to xeric vegetation in a meadow in Utah.

- Walter P Cottam and Stewart (1940). A shift from meadow grasses to junipers was documented and related to gully erosion in a meadow in Utah.

- Darrouzet-Nardi, D'Antonio, and Dawson (2006). Sagebrush in meadows of the Kern Plateau expanded its range owing to gully erosion and lower water-table elevations.

- Debinski, Wickham, Kindscher, Caruthers, and Germino (2010). Vegetation changes during drought in meadows in Yellowstone National Park were documented and related to hydrologic conditions.

- Hammersmark, Rains, Wickland, and Mount (2009). Plant communities following plug-and-pond restoration of Bear Meadow in Lassen County followed hydrologic gradients.

- Hammersmark, Dobrowski, Rains, and Mount (2010). A model was used to show an expansion of suitable habitat for mesic vegetation and a decrease in suitable habitat for xeric vegetation following restoration of a wet meadow on Bear Creek in Lassen County.

C. Meadow evapotranspiration in the western United States

The publications listed for this topic provide information on rates of meadow evapotranspiration (ET). ET increases after restoration, and may therefore decrease streamflow downstream during summer.

- Borrelli and Burman (1982). Monthly ET rates in wet meadows ranged from 2.8 to 25.0 cm during growing season.

- Loheide II and Gorelick (2005). ET in eroded meadows in the Feather River watershed ranged from 1.5 to 4 mm/day. ET in restored meadows ranged from 5 to 6.5 mm/day.

- Lowry and Loheide (2010). ET from groundwater comprised a large proportion of total wet-meadow ET, and reached rates of roughly 3 mm/day.

- Sanderson and Cooper (2008). Wet-meadow ET from groundwater was distinguished from total ET, and was found to be related to depth to the water table. Results from a variety of models were compared and assessed. Daily actual ET ranged from roughly 1 to 9 mm/day for wet meadows.

- Steinwand, Harrington, and Or (2006). ET of meadows in the Owens Valley near the Inyo NF was evaluated throughout annual cycles. Total growing season ET ranged from 53 to 646 mm. In wet alkali meadows with shallow water tables, groundwater supplied 60 to 81% of total ET. Use of groundwater by plants was correlated with water-table depth and leaf-area index.

D. Hydraulics of flow between bedrock and meadow aquifers in the western United States

The articles listed under this topic concern the hydrologic relations between meadow aquifers and their surrounding bedrock aquifers and watersheds. The hydrologic and hydraulic connenctions between meadows and their watersheds are now widely recognized, and any analysis of restoration effects must consider how water flows from hillslopes through meadows to streams.

- Atekwana and Richardson (2004). The source of meadow groundwater was found to be groundwater discharged from the surrounding watershed through bedrock.

- B. R. Hill (1990). An eroded meadow in Nevada allowed direct discharge of groundwater from fractured bedrock to an incised gully. Meadow alluvium had lower permeability than surrounding bedrock, and may have restricted groundwater discharge prior to erosion of the gully.

- B. Hill and Mitchell-Bruker (2010). This comment and accompanying reply (see Loheide and others, 2009, below) address the issue of the relative permeability of meadow alluvium and surrounding bedrock, and implications for streamflow regimen.

- Jewett, Lord, Miller, and Chambers (2004). Upward vertical hydraulic gradients of meadows in central Nevada were the result of heterogeneities in meadow alluvium that caused variations in permeability.

- Loheide II et al. (2009). Lower permeability of meadow alluvium, higher rates of groundwater inflow, and a high ratio of lateral to basal groundwater inflow all tend to result in higher meadow water-table elevations.

- Lowry, Deems, Loheide, and Lundquist (2010). Groundwater levels in Tuolumne Meadows in Yosemite NP were found to be controlled by hillslope sources of snowmelt runoff, snowmelt on the meadow surface, and stream recharge.

E. Meadow stratigraphy

The following publications provide information on meadow alluvium, including information useful for inferring hydraulic properties such as specific yield and permeability.

- Anderson and Smith (1994). Nine meadows in the central and southern Sierra Nevada were examined for this study. All had surficial peat deposits of roughly 0.5 to 2 m thickness, and most had subsurface strata composed of fine-grained organic silts with thickness of 1 to 2 m.

- Koehler and Anderson (1994). The stratigraphy of a meadow on the Sierra NF was composed mostly of silty sand, sand, and gravel, with minor amounts of clay and silty clay and no peat or other highly organic strata.

- Wood (1975). This monograph includes a wealth of information on meadow stratigraphy, origins, stability, erosion, groundwater dynamics, evapotranspiration, plant ecology, and chronology.

F. Sources of streamflow in meadows in the Western U.S.

Several studies, although not directly focused on streamflow, have provided qualitative information on sources of streamflow within meadows and the hydrologic role of meadows within watersheds. These studies have all described meadows as sources of surface water, either as headwater sources or as locations where streamflow is augmented. These observations indicate that meadows often have groundwater discharge rates in excess of evapotranspiration rates. Most of these observations were made in uneroded meadows.

- Elliott, Beck, and Prudic (2006). Streamflow was reported to increase within alluvial meadows in or near Great Basin National Park the Snake Range in Nevada. Increases in flow through meadows were reported both for snowmelt and baseflow periods.

- Jin, Siegel, Lautz, and Lu (2012). Storage and mixing of groundwater in a headwater meadow wetland was found to be an important control on streamflow regimen in Cherry Creek in the Wind River Range in Wyoming.

- Lord, Jewett, Miller, Germanoski, and Chambers (2011). Meadows in central Nevada mountain ranges were described as groundwater discharge zones supplying streams.

- Payn, Gooseff, McGlynn, Bencala, and Wondzell (2012). Baseflow increased substantially along Upper Tenderfoot Creek in the northern Rocky Mountains along a reach within a large meadow. This increase in flow through the meadow was not attributable to any known bedrock feature.

- Slack (1967). The source of Birch Creek in the White Mountains of California was a small wet meadow. Discharge decreased downstream of the meadow as the stream flowed towards the arid Deep Springs Valley.

G. Groundwater hydraulics of alluvial aquifers with low-permeability organic strata in other geographic areas

Many meadows in the Sierra Nevada have layers of decomposed peat at their surfaces or buried within alluvial strata. The following articles describe the effects of similar low-permeability organic strata on groundwater-surface water relations in other parts of the world, but have relevance for our understanding of Sierra Nevada meadow hydrology.

- Bowden, Fahey, Ekanayake, and Murray (2001). Water storage in bog peats was insufficient to support baseflows for longer than a few days in a New Zealand watershed.

- Branfireun and Roulet (1998). Groundwater emerging below a peat layer maintained baseflow in a stream in a small headwater wetland in Ontario.

- Langhoff, Rasmussen, and Christensen (2006). A peat layer below an alluvial streambed was found to limit groundwater discharge to the stream despite a large hydraulic gradient.

- McGlynn, McDonnell, Shanley, and Kendall (1999). Saturated hydraulic conductivity of peat ranged from 141 to 267 mm/hr (4 x 10-3 to 7 x 10-3 cm/s) in the riparian zone, and peat was underlain by a much lower conductivity till layer. Steep upward hydraulic gradients were observed in the riparian zone, and were related to streamflow. Low permeability layers caused a “backup” of flow in the riparian zone with increased hydraulic gradients.

- O'Brien (1988). Low-permeability organic wetland sediments can significantly influence groundwater flow patterns and discharge. Destruction of wetlands may result in decreased hydraulic heads, water table declines, and altered streamflow regimen.

- Reeve, Siegel, and Glaser (2000). The extent of upwardly vertical flow and vertical hydraulic gradients in peatlands was controlled by permeability contrasts between peat and underlying mineral soil.

- Vidon and Hill (2004). Saturated permeability of peat was determined to be 10 -5 cm/s. Horizontal/vertical permeability anisotropy in peats can range from 0 to 1,000. Low-permeability peats caused groundwater flow to be refracted upward toward stream channels and flood plains, resulting in year-long surface saturation at groundwater discharge zones.

- Wong, Hashim, and Ali (2009). Vertical hydraulic conductivity of peat ranged from 10-3 to 10-6 cm/s, and was lower for amorphous than fibrous peat.

H. Groundwater hydraulics of alluvial aquifers with low-permeability non-organic confining strata in other geographic areas

The publications listed below describe groundwater-surface water interactions affected by nonorganic low-permeability strata in other areas. These studies have relevance for some Sierran meadows owing to their descriptions of interactions between confined riparian aquifers and streams.

- Andersen and Acworth (2009). Lithologic heterogeneities that determine permeability were major determinants of patterns of groundwater discharge to a stream.

- Banks et al. (2009). Deep groundwater flow through fractured metamorphic bedrock was a major source of streamflow.

- D'Amore, Stewart, Huddleston, and Glasmann (2000). A confining layer composed of smectite clays resulted in artesian conditions in a wetland near Corvallis.

- Katsuyama, Ohte, and Kabeya (2005). Groundwater flow through weathered granite was an important source for a headwater riparian zone and for streamflow in a small mountainous watershed in Japan. Saturated hydraulic conductivity of unweathered granitic bedrock was roughly 6 x 10-4 cm/s, while weathered bedrock had a permeability 2 orders of magnitude higher.

- Konrad (2006). Permeability contrasts in alluvial aquifers were found to be one of 3 major factors affecting the magnitudes of flows between rivers and aquifers in the Columbia River basin.

- Morrice, Valett, Dahm, and Campana (1997). The flow direction of groundwater discharging to an alluvial stream was related to local variation in hydraulic gradients.

- Salve and Tokunaga (2002). Stratigraphic heterogeneities and varying permeabilities within valley alluvium in the central Coast Ranges resulted in temporary confining conditions that produced vertically-upward flow and exfiltration of groundwater.

- Urbano, Waldron, Larsen, and Shook (2006). A 3-dimensional steady-state groundwater model was used to evaluate the effects of an upper confining clay stratum on groundwater discharge to a stream. The results showed that groundwater discharge to the stream increased sharply at the upstream boundary of the confining unit. The model was also used to evaluate the effects of river entrenchment that breached the confining layer. Entrenchment resulted in sharp increases in groundwater discharge to the stream.

I. Alluvial channel incision (gully erosion) effects on streamflow in other geographic areas

These studies are summarized owing to expected similarities between the effects of channel incision of alluvial aquifers in various areas worldwide with meadow erosion in the western U.S.

- Costa and de Almeida Prado Bacellar (2007). Gully erosion of alluvial and colluvial valleys resulted in higher peak flows and lower base flows. See reference number 4. below for additional analyses of the effects of gully erosion on confined groundwater flows.

- de AP Bacellar, Netto, and Lacerda (2005). Gully erosion was related to breaching of a confining clay layer overlying a more permeable saprolite aquifer by roads and ditches.

- Larkin and Sharp (1992). Alluvial aquifers in various locations throughout the United States were classified either as baseflow (groundwater flow perpendicular to the stream channel) or underflow (groundwater flow parallel to the stream). Factors important in determining the relative proportions of groundwater flowing toward the channel or down the axis of the valley included channel gradient, channel depth, and sinuosity.

- Nogueras, Burjachs, Gallart, and Puigdefabregas (2000). This study infers a natural groundwater storage function for valley fills that remain uneroded by gullies. However, no data on this topic are presented.

- Rutherfurd, Hoang, Prosser, Abernethy, and Jayasuriya (1996). Gully erosion of alluvial headwater valleys in Australia increased flood peaks by 12 to 20% and decreased time to peak by 20 to 24% for the 100-year and 1-year floods, respectively.

- Schilling, Zhang, and Drobney (2004). Stream incision of 3 m into an alluvial valley floor increased flood peaks and reduced the time between peak rainfall and streamflow. Groundwater storage was reduced. Hydraulic gradients toward the stream were increased.

- Shields Jr, Knight, and Cooper (1994). An unincised reference stream had higher autumn baseflow than 3 incised streams in Mississippi.

J. Bank recharge and overbank recharge in alluvial aquifers

One of the major questions related to the hydrologic functions of eroded and restored or intact meadows is the relative importance of bank recharge and overbank recharge. Both types of recharge occur when the water surface of the stream is higher than the water table in the surrounding alluvial aquifer. Bank recharge is likely to be most effective in eroded meadows, where incised channels confine almost all peak flows. Overbank recharge is likely to be most effective in uneroded or restored meadows, where flood flows can spread across valley floors. Both bank and overbank recharge have been hypothesized to reduce peak flows and provide groundwater that sustains dry season streamflow, but the amounts of water stored by each process, and the changes in storage that might result from meadow erosion or restoration, have not been rigorously investigated.

- Doble, Crosbie, Smerdon, Peeters, and Cook (2012). The volume of overbank recharge increases with hydraulic conductivity of alluvial aquifers, stream stage, and duration of peak flows, and decreases with increasing hydraulic gradients oriented toward stream channels. Overbank recharge was limited both by available unsaturated storage capacity and the permeability of the alluvial aquifer.

- Simpson, Meixner, and Hogan (2013). Flood recharge along losing alluvial reaches in Arizona supplies downstream baseflow for several years after large long-duration floods.

- Whiting and Pomeranets (1997). The volume of stored groundwater resulting from bank storage that can contribute to dry-season streamflow is proportional to valley width, bank height, and specific yield of alluvium. Duration of groundwater discharge is proportional to valley width and inversely proportional to hydraulic conductivity of alluvium. The duration of groundwater discharge following bank recharge can range from days in gravel aquifers to decades in clay aquifers.

K. Hydrologic functions of headwater wetlands in other geographic areas

Although many more publications are available, these selected articles are summarized here to show that the hydrologic functions of small alluvial headwater wetlands are not well understood in many areas worldwide. These articles illustrate approaches that have been used to evaluate streamflow regulation in headwater wetlands and demonstrate that wetlands that appear to be generally similar may have significantly different hydrologic behaviors.

- Andrew Bullock (1992). This article reviews published research on the hydrologic functions of dambos (small alluvial headwater wetlands in Africa), notes a lack of consensus of the effects of dambos on low flows, and proposes that dambos may reduce baseflows.

- A. Bullock and Acreman (2003). This article reviews published information on the subject and classifies results based on types of wetlands worldwide. Most studies of wetland effects on baseflows showed decreases.

- Jencso, McGlynn, Gooseff, Bencala, and Wondzell (2010). The size of riparian zones was found to significantly effect their role in affecting the magnitude and timing of streamflow.

- Montreuil, Cudennec, and Merot (2011). An upstream riparian wetland had lower hydraulic conductivity, higher and more vertical (upward) groundwater flow gradients, longer and higher periods of saturation, and greater groundwater discharge to the stream channel in comparison to a downstream wetland in Brittany (France). The downstream wetland had a more deeply incised channel.

- Morley, Reeve, and Calhoun (2011). Small headwater wetlands were found to regulate the discharge of shallow groundwater from hillslopes to streams and thereby increase the volume and duration of baseflows in a central Maine watershed.

- Prosser, Chappell, and Gillespie (1994). Swampy meadows were inferred to increase peak flows owing to greater proportions of saturated overland flow relative to valleys eroded by gullies. Effects of meadows or erosion on baseflows were not assessed.

- Riddell, Lorentz, and Kotze (2010). Illuvial low-permeability “clay plugs” were found to be important features controlling groundwater flow in an eroding headwater wetland in South Africa.

- Smakhtin and Batchelor (2005). Regional flow-duration curves and paired (upstream/downstream) streamgages were used to evaluate streamflow regulation in a large flood-plain wetland similar in South Africa. The wetland had many similarities to alluvial meadows in the western U.S. The wetland was found to attenuate flood peaks and increase baseflows.

- Von Der Heyden (2004). This paper reviews available information on hydrology of dambos (small alluvial headwater wetlands in Africa) and describes the current lack of consensus on their hydrological functions, including maintenance of low flows.

Full Citation List

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