MOKELUMNE WATERSHED AVOIDED COST ANALYSIS:

Why Sierra Fuel Treatments Make Economic Sense

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FOREST SERVICE U S DEPARTMENT OF AGRICULTURE

Appendix I: Bibliography on Hydrologic Effects of Meadow Restoration in the Sierra Nevada

I.1 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 9 major topics (A to I). 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 E, which are specific to mountain meadows in the western United States. Topics G through I 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.

I.2 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.

I.2.1 Cornwell, Kevin, and Brown, Kamala, 2008, Physical and hydrological characterization of Clark's Meadow in the Last Chance Watershed of Plumas County: Report to the Natural Heritage Institute, Mountain Meadows IRWMP, California State University Sacramento, Department of Geology, 38 pp.

http://ceic.resources.ca.gov/catalog/SacramentoRiverWatershedData/PhysicalAndHydrologicalCharacterizationOfClarksMeadow.html

Plug and pond meadow restoration increased groundwater storage. Effects on streamflow were not evaluated.

I.2.2 DeBano, L.F., and Schmidt, L.J., 1989, Improving southwestern riparian areas through watershed management: USDA Forest Service General Technical Report RM-182, 33pp.

http://www.treesearch.fs.fed.us/pubs/37647

A case study in Colorado is described in which ephemeral or intermittent flows were converted to perennial flows by restoration of gullied channels in alluvial headwater valleys in the Alkalai Creek watershed described by Heede (1979; see below). Recovery of streamflow was not observed until after 12 years of project implementation and 7 post-project years. Although perennial flow was restored to the downstream reach of the project, upstream channels remained ephemeral.

I.2.3 Elmore, Wayne, and Beschta, R.L., 1987, Riparian areas: perceptions in management: Rangelands 9(6):260-265.

http://www.rmrs.nau.edu/awa/ripthreatbib/elmore_beschta_riperianareas.pdf

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.

I.2.4 Hammersmark, C., Rains, M., and Mount, J., 2008, Quantifying the hydrological effects of stream restoration in a montane meadow, northern California, USA: River Research and Applications 24(6): 735-753.

http://onlinelibrary.wiley.com/doi/10.1002/rra.1077/abstract

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.

I.2.5 Heede, B.H., 1979, Deteriorated watersheds can be restored: a case study: Environmental Management 3(3):271-281

http://www.springerlink.com/content/g4rg7745761vgu56/

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.

I.2.6 Klein, L.R., Clayton, S.R., Alldredge, J.R., and Goodwin, Peter, 2007, Long-term monitoring and evaluation of the Lower Red River meadow restoration project, Idaho, USA: Restoration Ecology 15(2):223-239.

http://onlinelibrary.wiley.com/doi/10.1111/j.1526-100X.2007.00206.x/pdf

Evaluation of restoration of a large meadow in Idaho showed that restoration resulted in increased duration, extent, and volume of overbank flooding.

I.2.7 Liang, L., Kavvas, M.L., Chen, Z.Q., Anderson, M., Ohara, N., Wilcox, J., and Mink, L., 2007, Modeling river restoration impact on flow and sediment in a California watershed: Proceedings of ASCE World Environmental and Water Resources Congress, ed. by. Karen C. Kabbes, Conf. in Tampa, Florida, May, 2007.

Not available via internet.

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.

I.2.8 Loheide, S.P. II, and Gorelick, S.M., 2006, Quantifying stream-aquifer interactions through the analysis of remotely sensed thermographic profiles and in situ temperature histories: Environmental Science and Technology 40(10):3336-3341.

http://www.clas.ufl.edu/users/jbmartin/website/Classes/Surface_Groundwater/Class%203/Loheide%20and%20Gorelick%20Environ%20Sci%20Tech%202006%20Hypor%20and%20T.pdf

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).

I.2.9 Loheide, S.P. II, and Gorelick, S.M., 2007, Riparian hydroecology: a coupled model of the observed interactions between groundwater flow and meadow vegetation patterning: Water Resources Research, vol. 43, W07414

http://www.agu.org/journals/ABS/2007/2006WR005233.shtml

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.

I.2.10 Loheide, S.P., and Booth, E.G., 2010, Effects of changing channel morphology on vegetation, groundwater, and soil moisture regimes in groundwater-dependent ecosystems: Geomorphology (article in press).

http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V93-50106MJ-2&_user=4250274&_coverDate=05%2F05%2F2010&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_searchStrId=1551700173&_rerunOrigin=google&_acct=C000052423&_version=1&_urlVersion=0&_userid=4250274&md5=5847b8885034e26e3f9376a1e9293daf&searchtype=a

Effects of channel incision and widening on vegetation and groundwater in alluvial aquifers such as meadows were evaluated. Effects on streamflow were not analyzed.

I.2.11 Ponce, V.M., and Lindquist, D.S., 1990, Management strategies for baseflow augmentation: Proceedings, ASCE Irrigation and Drainage Division, Watershed Management Symposium, Durango, Colorado, July 9-11, 1990.

http://saltonsea.sdsu.edu/watershedplanbaseflowaug313.html

Provides examples of several western mountain meadows where restoration, primarily with check dams, converted ephemeral channels to perennial flow.

I.2.12 Swanson, Sherman, Franzen, Dave, and Manning, Mary, 1987, Rodero Creek: rising water on the high desert: Journal of Soil and Water Conservation 42(6):405-407.

www.jswconline.org/content/42/6/405.extract

Meadow restoration with check dams in northwestern Nevada transformed about a mile of intermittent channel to perennial flow.

I.2.13 Tague, Christina, Valentine, Scott, and Kotchen, Matthew, 2008, Effect of geomorphic channel restoration on streamflow and groundwater in a snowmelt-dominated watershed: Water Resources Research 44, W10415, 10 pp.

http://environment.yale.edu/kotchen/pubs/stream.pdf

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.

I.3 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.

I.3.1 Allen-Diaz, B.H., 1991, Water table and plant species relationships in Sierra Nevada meadows: American Midland Naturalist 126:30-43.

http://www.jstor.org/stable/2426147

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

I.3.2 Cottam, W.P., 1929, Man as a biotic factor illustrated by recent floristic and physiographic changes at the Mountain Meadows, Washington County, Utah: Ecology 10(4):361-363

http://www.esajournals.org/doi/abs/10.2307/1931143

Historical observations were used to illustrate relations between human land disturbance, meadow erosion, and subsequent shifts to xeric vegetation in a meadow in Utah.

I.3.3 Cottam, W.P., and Stewart, George, 1940, Plant succession as a result of grazing and of meadow desiccation by erosion since settlement in 1862: Journal of Forestry 38:613-626.

http://www.ingentaconnect.com/content/saf/jof/1940/00000038/00000008/art00004

A shift from meadow grasses to junipers was documented and related to gully erosion in a meadow in Utah.

I.3.4 Darroutzet-Nardi, Anthony, D'Antonio, C.M., and Dawson, T.E., 2006, Depth of water acquisition by invading shrubs and resident herbs in a Sierra Nevada meadow: Plant and Soil 285:31-43

http://anthony.darrouzet-nardi.net/works/Darrouzet-Nardi2006b.pdf

Sagebrush in meadows of the Kern Plateau expanded its range owing to gully erosion and lower water-table elevations.

I.3.5 Debinski, D.M., Wickham, Hadley, Kindscher, Kelly, Caruthers, J.C., and Germino, Matthew, 2010, Montane meadow change during drought varies with background hydrologic regime and plant functional group: Ecology 91(6):1672-1681.

http://www.esajournals.org/doi/abs/10.1890/09-0567.1

Vegetation changes during drought in meadows in Yellowstone National Park were documented and related to hydrologic conditions.

I.3.6 Hammersmark, C.T., Rains, M.C., Wickland, A.C., and Mount, J.F., 2009, Vegetation and water-table relationships in a hydrologically restored riparian meadow: Wetlands 29(3):785-797.

http://www.bioone.org/doi/abs/10.1672/08-15.1

Plant communities following plug-and-pond restoration of Bear Meadow in Lassen County followed hydrologic gradients.

I.3.7 Hammersmark, C.T., Dobrowski, S.Z., Rains, M.C., and Mount, J.F., 2010, Simulated effects of stream restoration on the distribution of wet-meadow vegetation: Restoration Ecology 18(6):882-893.

http://onlinelibrary.wiley.com/doi/10.1111/j.1526-100X.2009.00519.x/pdf

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.

I.4 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.

I.4.1 Borrelli, John, and Burman, R.D., 1982, Evapotranspiration from heterogeneous mountain meadows: Water Resources Series No. 86, Wyoming Water Research Center, University of Wyoming, Laramie, WY, 31 pp.

http://library.wrds.uwyo.edu/wrs/wrs-86/abstract.html

Monthly ET rates in wet meadows ranged from 2.8 to 25.0 cm during growing season.

I.4.2 Loheide, S.P. II, and Gorelick, S.M., 2005, A local-scale, high-resolution evapotranspiration mapping algorithm (ETMA) with hydroecological applications at riparian meadow restoration sites: Remote sensing of Environment 98: 182-200.

http://www.feather-river-crm.org/project-files/ETPaper.pdf

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.

I.4.3 Lowry, C.S., and Loheide, S.P. II, 2010, Groundwater-dependent vegetation: quantifying the groundwater subsidy: Water Resources Research 46, W06202, 8 pp.

http://www.agu.org/pubs/crossref/2010/2009WR008874.shtml

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

I.4.4 Sanderson, J.S., and Cooper, D.J., 2008, Ground water discharge by evapotranspiration in wetlands of an arid intermountain basin: Journal of Hydrology 351: 344-359.

http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V6C-4RGM0V9-3&_user=4250274&_coverDate=04%2F15%2F2008&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_searchStrId=1551778614&_rerunOrigin=google&_acct=C000052423&_version=1&_urlVersion=0&_userid=4250274&md5=215d32ef4b2418a74f0259b74b1010a4&searchtype=a

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.

I.4.5 Steinwand, A.L., Harrington, R.F., and Or, D., 2006, Water balance for Great Basin phreatophytes derived from eddy covariance, soil water, and water table measurements: Journal of Hydrology 329(3-4):595-605.

http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V6C-4K0FK06-2&_user=4250274&_coverDate=10%2F15%2F2006&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_searchStrId=1551786995&_rerunOrigin=google&_acct=C000052423&_version=1&_urlVersion=0&_userid=4250274&md5=241899b90510761cee444c14b943dd7a&searchtype=a

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.

I.5 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 connections 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.

I.5.1 Atekwana, E.A., and Richardson, D.S., 2004, Geochemical and isotopic evidence of a groundwater source in the Corral Canyon meadow complex, central Nevada, USA: Hydrological Processes 18:2801-2815.

http://onlinelibrary.wiley.com/doi/10.1002/hyp.1495/abstract

The source of meadow groundwater was found to be groundwater discharged from the surrounding watershed through bedrock.

I.5.2 Hill, B.R., 1990, Groundwater discharge to a headwater valley, northwestern Nevada, USA: Journal of Hydrology 113: 265-283.

http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V6C-4876D4N-4M&_user=4250274&_coverDate=02%2F28%2F1990&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_searchStrId=1554647423&_rerunOrigin=google&_acct=C000052423&_version=1&_urlVersion=0&_userid=4250274&md5=502b6c0172dbaad5b05795caeee929eb&searchtype=a

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.

I.5.3 Hill, B.R., and Mitchell-Bruker, Sherry, 2010, Comment on "A framework for understanding the hydroecology of impacted wet meadows in the Sierra Nevada and Cascade Ranges, California, USA": paper published in *Hydrogeology Journal* (2009) 17:229–246, by Steven P. Loheide II, Richard S. Deitchman, David J. Cooper, Evan C. Wolf, Christopher T. Hammersmark, Jessica D. Lundquist: Hydrogeology Journal 18(7):1741-1743.

http://www.springerlink.com/content/5077179318n71301/

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.

I.5.4 Jewett, D.G., Lord, M.L., Miller, J.R., and Chambers, J.C., 2004, Geomorphic and hydrologic controls on surface and subsurface flow regimes in riparian meadow ecosystems, Chapter 5, p. 124-161, in: Great Basin Riparian Ecosystems, Chambers, J.C., and Miller, J.R. (eds.), Society for Ecological Restoration International, Island Press, Covelo, CA.

http://books.google.com/books?id=irAQvednci4C&pg=PA124&lpg=PA124&dq=jewett+chambers+great+basin+riparian+ecosystems+2004&source=bl&ots=qve4wBC7DK&sig=y8tm15LfWmr9mbewrWyUz5YaTfk&hl=en&ei=0U_tTNKOL4T0swPDzcCqBw&sa=X&oi=book_result&ct=result&resnum=1&ved=0CBkQ6AEwAA#v=onepage&q&f=false

Upward vertical hydraulic gradients of meadows in central Nevada were the result of heterogeneities in meadow alluvium that caused variations in permeability.

I.5.5 Loheide, S.P. II, Deitchman, R.S., Cooper, D.J., Wolf, E.C., Hammersmark, C.T., and Lundquist, J.D., 2009, A framework for understanding the hydroecology of impacted wet meadows in the Sierra Nevada and Cascade Ranges, California, USA: Hydrogeology Journal 17:229-246.

http://www.ingentaconnect.com/content/klu/10040/2009/00000017/00000001/00000380

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.

I.5.6 Lowry, C.S., Deems, J.S., Loheide, S.P. II, and Lundquist, J.D., 2010, Linking snowmelt-derived fluxes and groundwater flow in a high elevation meadow system, Sierra Nevada Mountains, California: Hydrological Processes 24(20):2821-2833.

http://onlinelibrary.wiley.com/doi/10.1002/hyp.7714/abstract

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.

I.5.7 Payn, R.A., Gooseff, M.N., McGlynn, B.L., Bencala, K.E., and Wondzell, S.M., 2012, Exploring changes in the spatial distribution of stream baseflow generation during a seasonal recession: Water Resources Research Vol. 48, W04519, 15 pp.

http://watershed.montana.edu/hydrology/Home_files/Payn_etal_baseflow_generation_WRR_2012.pdf

A major increase in summer baseflow was noted within a large meadow in the northern Rocky Mountains despite a lack of any change in bedrock.

I.6 Meadow stratigraphy

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

I.6.1 Anderson, R.S., and Smith, S.J., 1994, Paleoclimatic interpretations of meadow sediment and pollen stratigraphies from California: Geology, vol. 22, p. 723-726.

http://geology.geoscienceworld.org/cgi/content/abstract/22/8/723

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.

I.6.2 Koehler, P.A., and Anderson, R.S., 1994, The paleoecology and stratigraphy of Nichols Meadow, Sierra National Forest, California, USA: Palaeogeography, Palaeoclimatology, Palaeoecology 112: 1-17.

http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V6R-4894VG2-S&_user=4250274&_coverDate=11%2F30%2F1994&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_searchStrId=1553447910&_rerunOrigin=google&_acct=C000052423&_version=1&_urlVersion=0&_userid=4250274&md5=4a11b509278ecdc4c64d2dfcbf2c2b06&searchtype=a

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.

I.6.3 Wood, S.H., 1975, Holocene stratigraphy and chronology of mountain meadows, Sierra Nevada, California: USDA-Forest Service Earth Surface Monograph 4, Pacific Southwest Region.

http://thesis.library.caltech.edu/5570/

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

I.7 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.

I.7.1 Bowden, W.B., Fahey, B.D., Ekanayake, J., and Murray, D.L., 2001, Hillslope and wetland hydrodynamics in a tussock grassland, South Island, New Zealand: Hydrological Processes 15: 1707-1730.

http://onlinelibrary.wiley.com/doi/10.1002/hyp.235/abstract

Water storage in bog peats was insufficient to support baseflows for longer than a few days in a New Zealand watershed.

I.7.2 Branfireun, B.A., and Roulet, N.T., 1998, The baseflow and storm flow hydrology of a Precambrian shield headwater peatland: Hydrological Processes 12: 57-72.

http://onlinelibrary.wiley.com/doi/10.1002/(SICI)1099-1085(199801)12:1%3C57::AID-HYP560%3E3.0.CO;2-U/abstract

Groundwater emerging below a peat layer maintained baseflow in a stream in a small headwater wetland in Ontario.

I.7.3 Langhoff, J.H., Rasmussen, K.R., and Christensen, Steen, 2005, Quantification and regionalization of groundwater-surface water interaction along an alluvial stream: Journal of Hydrology 320:342-358.

http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V6C-4H6GPWC-1&_user=4250274&_coverDate=04%2F15%2F2006&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_acct=C000052423&_version=1&_u

rlVersion=0&_userid=4250274&md5=fc5b890f8784d251605da642039c1047&searchtype=a

A peat layer below an alluvial streambed was found to limit groundwater discharge to the stream despite a large hydraulic gradient.

I.7.4 McGlynn, B.L., McDonnell, J.J., Shanley, J.B., and Kendall, C., 1999, Riparian zone flowpath dynamics during snowmelt in a small headwater catchment: Journal of Hydrology 222:75-92.

http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V6C-3XBTSHK-6&_user=4250274&_coverDate=09%2F13%2F1999&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_searchStrId=1552938308&_rerunOrigin=google&_acct=C000052423&_version=1&_urlVersion=0&_userid=4250274&md5=29c4c2acd4605cc06478a68b04eef6b9&searchtype=a

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.

I.7.5 O'Brien, A.L., 1988, Evaluating the cumulative effects of alteration on New England wetlands: Environmental Management 12(5):627-636.

http://www.springerlink.com/content/rtp5139133t80260/

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.

I.7.6 Reeve, A.S., Siegel, D.I., and Glaser, P.H., 2000, Simulating vertical flow in large peatlands: Journal of Hydrology 227: 207-217.

http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V6C-3YRVDK7-G&_user=4250274&_coverDate=01%2F31%2F2000&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_searchStrId=1553409453&_rerunOrigin=google&_acct=C000052423&_version=1&_urlVersion=0&_userid=4250274&md5=72bf0bffc9e96a807306afc2278d3a99&searchtype=a

The extent of upwardly vertical flow and vertical hydraulic gradients in peatlands was controlled by permeability contrasts between peat and underlying mineral soil.

I.7.7 Vidon, P.G.F., and Hill, A.R., 2004, Landscape controls on the hydrology of stream riparian zones: Journal of Hydrology 292:210-228.

http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V6C-4BYNR6V-B&_user=4250274&_coverDate=06%2F15%2F2004&_rdoc=1&_fmt=high&_orig=searc

h&_origin=search&_sort=d&_docanchor=&view=c&_acct=C000052423&_version=1&_urlVersion=0&_userid=4250274&md5=111728ffa3e387a8125dac8075830be5&searchtype=a

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.

I.7.8 Wong, L.S., Hashim, R., and Ali, F.H., 2009, A review on hydraulic conductivity and compressibility of peat: Journal of Applied Sciences 9(18):3207-3218.

http://www.scialert.net/pdfs/jas/2009/3207-3218.pdf

Vertical hydraulic conductivity of peat ranged from 10^{-3} to 10^{-6} cm/s, and was lower for amorphous than fibrous peat.

I.8 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.

I.8.1 Andersen, M.S., and Acworth, R.I., 2009, Stream-aquifer interactions in the Maules Creek catchment, Namoi Valley, New South Wales, Australia: Hydrogeology Journal 17: 2005-2021.

http://www.springerlink.com/content/rtp5139133t80260/

Lithologic heterogeneities that determine permeability were major determinants of patterns of groundwater discharge to a stream.

I.8.2 Banks, E.W., Simmons, C.T., Love, A.J., Cranswick, R., Werner, A.D., Bestland, E.A., Wood, M., and Wilson, T., 2009, Fractured bedrock and saprolite hydrogeologic controls on groundwater/surface water interaction: a conceptual model (Australia): Hydrogeology Journal 17:1969-1989.

http://www.springerlink.com/content/rtp5139133t80260/

Deep groundwater flow through fractured metamorphic bedrock was a major source of streamflow.

I.8.3 D'Amore, D.V., Stewart, S.R., Huddleston, J.H., and Glasmann, J.R., 2000, Stratigraphy and hydrology of the Jackson-Frazier wetland, Oregon: Soil Science Society of America Journal 64:1535-1543.

https://www.soils.org/publications/sssaj/articles/64/4/1535

A confining layer composed of smectite clays resulted in artesian conditions in a wetland near Corvallis.

I.8.4 Katsuyama, Masanori, and Ohte, Nobuhito, 2005, Effects of bedrock permeability on hillslope and riparian groundwater dynamics in a weathered granite catchment: Water Resources Research vol. 41, W01010, 11 pp.

http://www.agu.org/journals/ABS/2005/2004WR003275.shtml

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 6×10^{-4} cm/s, while weathered bedrock had a permeability 2 orders of magnitude higher.

I.8.5 Konrad, C.P., 2006, Location and timing of river-aquifer exchanges in six tributaries to the Columbia River in the Pacific Northwest of the United States: Journal of Hydrology 329: 444-470.

http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V6C-4JRM0NR-3&_user=4250274&_coverDate=10%2F15%2F2006&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_searchStrId=1627378435&_rerunOrigin=google&_acct=C000052423&_version=1&_urlVersion=0&_userid=4250274&md5=6574304fe165ab648d0762222cf5acd7&searchtype=a

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.

I.8.6 Morrice, J.A., Valett, H.M., Dahm, C.N., and Campana, M.E., 1997, Alluvial characteristics, groundwater-surface water exchange and hydrological retention in headwater streams: Hydrological Processes 11:253-267.

http://onlinelibrary.wiley.com/doi/10.1002/(SICI)1099-1085(19970315)11:3%3C253::AID-HYP439%3E3.0.CO;2-J/abstract

The flow direction of groundwater discharging to an alluvial stream was related to local variation in hydraulic gradients.

I.8.7 Salve, Rohit, and Tokunaga, T.T., 2002, Seepage response along an alluvial valley in a semi-arid catchment in north-central California: Hydrological Processes 16: 65-86.

http://onlinelibrary.wiley.com/doi/10.1002/hyp.285/abstract

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.

I.8.8 Urbano, Lensyl, Waldron, Brian, Larsen, Dan, and Shook, Heather, 2006, Groundwater-surface water interactions at the transition of an aquifer from unconfined to confined: Journal of Hydrology 321:200-212.

http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V6C-4H4T3CN-6&_user=4250274&_coverDate=04%2F30%2F2006&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_searchStrId=1552907627&_rerunOrigin=google&_acct=C000052423&_version=1&_urlVersion=0&_userid=4250274&md5=b1262a0da7f78b5aaface042a3c99d0c&searchtype=a

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.9 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.

I.9.1 Costa, F.M., and de Almeida Prado Bacellar, Luis, 2007, Analysis of the influence of gully erosion in the flow pattern of catchment streams, Southeastern Brazil: Catena 69: 230-238.

http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6VCG-4KDBM9F-1&_user=4250274&_coverDate=04%2F15%2F2007&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_acct=C000052423&_version=1&_urlVersion=0&_userid=4250274&md5=ed821e963953200e805e3ad171db9be0&searchtype=a

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.

I.9.2 De A.P. Bacellar, Coehlo Netto, A.L., and Lacerda, W.A., 2005, Controlling factors of gullying in the Maracuja Catchment, Southeastern Brazil: Earth Surface Processes and Landforms 30:1369-1385.

http://onlinelibrary.wiley.com/doi/10.1002/esp.1193/pdf

Gully erosion was related to breaching of a confining clay layer overlying a more permeable saprolite aquifer by roads and ditches.

I.9.3 Larkin, R.G., and Sharp, J.M., Jr., 1992, On the relationship between river-basin geomorphology, aquifer hydraulics, and ground-water flow direction in alluvial aquifers: Geological Society of America Bulletin 104(12): 1608-1620.

http://bulletin.geoscienceworld.org/cgi/content/abstract/104/12/1608

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.

I.9.4 Nogueras, Pascual, Burjachs, Francesc, Gallart, Francesc, and Puigdefabregas, Joan, 2000, Recent gully erosion in the El Cautivo badlands (Tabernas, SE Spain): Catena 40:203-215.

http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6VCG-40GJDN8-6&_user=4250274&_coverDate=06%2F15%2F2000&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_searchStrId=1606478070&_rerunOrigin=google&_acct=C000052423&_version=1&_urlVersion=0&_userid=4250274&md5=9d689683506fd8a80fc5a68242a7b4d2&searchtype=a

This study infers a natural groundwater storage function for valley fills that remain uneroded by gullies. However, no data on this topic are presented.

I.9.5 Rutherfurd, Ian, Hoang, Tam, Prosser, Ian, Abernethy, Bruce, and Jayasuriya, Nira, 1996, The impacts of gully networks on the time-to-peak and size of flood hydrographs, in: Hydrology and Water Resources Symposium 1996: Water and the Environment, Preprints of papers, p. 397-402.

http://search.informit.com.au/documentSummary;dn=364553489879848;res=IELENG>ISBN:0858256495

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.

I.9.6 Schilling, K.E., Zhang, Y.K., and Drobney, P., 2004, Water table fluctuations near an incised stream, Walnut Creek, Iowa: Journal of Hydrology 286(1-4), p. 236-248.

http://www.sciencedirect.com

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.

I.9.7 Shields, R.D., Jr., Knight, S.S., and Cooper, C.M., 1994, Effects of channel incision on baseflow stream habitats and fishes: Environmental Management 18(1):43-57.

http://www.springerlink.com/content/l8ph1q731j370186/fulltext.pdf

An unincised reference stream had higher autumn baseflow than 3 incised streams in Mississippi.

I.10 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.

I.10.1 Bullock, Andrew, 1992, Dambo hydrology in southern Africa—review and assessment: Journal of Hydrology 134(1-4):373-396.

http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V6C-48C7D50-5X&_user=4250274&_coverDate=06%2F30%2F1992&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_searchStrId=1554706096&_rerunOrigin=google&_acct=C000052423&_version=1&_urlVersion=0&_userid=4250274&md5=dcf5d0f9a6c5ef3c757a37140c0055c9&searchtype=a

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.

I.10.2 Bullock, Andy, and Acreman, Mike, 2003, The role of wetlands in the hydrological cycle: Hydrology and Earth Systems Sciences 7(3):358-389.

http://www.hydrol-earth-syst-sci.net/7/358/2003/hess-7-358-2003.html

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.

I.10.3 Jencso, K.G., McGlynn, B.L., Gooseff, M.N., Bencala, K.E., and Wondzell, S.M., 2010, Hillslope hydrologic connectivity controls riparian groundwater turnover: Implications of catchment structure for riparian buffering and stream water sources: Water Resources Research, vol. 46, W10524, 18 pp.

http://watershed.montana.edu/hydrology/Home_files/Jencso%20McGlynn%20et%20al%20%202009WR008818%20(1).pdf

The size of riparian zones was found to significantly affect their role in affecting the magnitude and timing of streamflow.

I.10.4 Montreuil, Olivier, Cudennec, Christophe, and Merot, Philippe, 2011, Contrasting behavior of two riparian wetlands in relation to their location in the hydrographic network: Journal of Hydrology 406: 39-53.

http://www.sciencedirect.com/science/article/pii/S0022169411003775

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.

I.10.5 Morley, T.R., Reeve, A.S., and Calhoun, A.J.K., 2011, The role of headwater wetlands in altering streamflow and chemistry in a Maine, USA catchment: Journal of the Water Resources Association 47(2): 337-349.

http://onlinelibrary.wiley.com/doi/10.1111/j.1752-1688.2010.00519.x/abstract

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.

I.10.6 Prosser, I.P., Chappell, John, and Gillespie, Richard, 1994, Holocene valley aggradation and gully erosion in headwater catchments, South-Eastern highlands of Australia: Earth Surface Processes and Landforms 19: 465-480.

http://onlinelibrary.wiley.com/doi/10.1002/esp.3290190507/pdf

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.

I.10.7 Riddell, E.S., Lorentz, S.A., and Kotze, D.C., 2010, A geophysical analysis of hydro-geomorphic controls within a headwater wetland in a granitic landscape, through ERI and IP: Hydrology and Earth System Sciences 14: 1697-1713.

http://www.hydrol-earth-syst-sci-discuss.net/7/1973/2010/hessd-7-1973-2010-print.pdf

Illuvial low-permeability "clay plugs" were found to be important features controlling groundwater flow in an eroding headwater wetland in South Africa.

I.10.8 Smakhtin, V.U., and Batchelor, A.L., 2005, Evaluating wetland flow regulating functions using discharge time-series: Hydrological Processes 19:1293-1305.

http://onlinelibrary.wiley.com/doi/10.1002/hyp.5555/pdf

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.

I.10.9 Von der Heyden, C.J., 2004, The hydrology and hydrogeology of dambos: a review: Progress in Physical Geography 28(4):544-564.

http://ppg.sagepub.com/content/28/4/544.abstract

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.

Mokelumne Watershed Avoided Cost Analysis: Why Sierra Fuel Treatments Make Economic Sense

Report Version 1.0

April 10, 2014

Citation Suggestion:

Buckley, M., N. Beck, P. Bowden, M. E. Miller, B. Hill, C. Luce, W. J. Elliot, N. Enstice, K. Podolak, E. Winford, S. L. Smith, M. Bokach, M. Reichert, D. Edelson, and J. Gaither. 2014. "Mokelumne watershed avoided cost analysis: Why Sierra fuel treatments make economic sense." A report prepared for the Sierra Nevada Conservancy, The Nature Conservancy, and U.S. Department of Agriculture, Forest Service. *Sierra Nevada Conservancy.* Auburn, California. Online: http://www.sierranevadaconservancy.ca.gov/mokelumne.

Disclaimer

This report is rich in data and analyses and may help support planning processes in the watershed. The data and analyses were primarily funded with public resources and are therefore available for others to use with appropriate referencing of the sources. This analysis is not intended to be a planning document.

The report includes a section on cultural heritage to acknowledge the inherent value of these resources, while also recognizing the difficulty of placing a monetary value on them. This work honors the value of Native American cultural or sacred sites, or disassociated collected or archived artifacts. This work does not intend to cause direct or indirect disturbance to any cultural resources.

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