# GROUNDWATER STORAGE AND FLUX IN A SMALL MONTANE MEADOW SYSTEM, SIERRA NEVADA, USA

Kevin Cornwell, Dept. of Geology, California State University, Sacramento, cornwell@csus.edu, ph. 916.278.6667, fax 916.278.4650 Kamala Brown, Dept. of Geology, California State University, Sacramento

**KEYWORDS**: groundwater, montane meadows, restoration, erosion, Sierra Nevada

## ABSTRACT

This paper summarizes our efforts to measure the potential groundwater storage capacity of a small, partially restored montane meadow and how that volume changes under various seasonal conditions. Volume calculations suggest that under peak recharge conditions as much as 335,328 $m^3$ of groundwater exist in the Meadow. This volume naturally decreases during the dry season as the Meadow dewaters to approximately 240,660 $m^3$ of stored groundwater, a net loss of about 29% from peak conditions. The degraded nature of the lower part of the Meadow however, causes more substantial groundwater loss throughout the dry season. If that condition was pervasive throughout the entire Meadow, groundwater loss would decrease the stored volume to about 139,276 $m^3$, a loss of an additional 29%. Unchecked stream erosion in the Meadow increases the loss of groundwater through dewatering during the dry season. Groundwater loss has substantial impact to the vegetation that anchors sediment to the floodplain and stream channel adversely affecting the natural flora and fauna of the area. Restoration activities reduce this loss in storage during seasonal dry times, promote higher groundwater levels throughout the year and reduce the range of fluctuation in those levels between seasons.

## INTRODUCTION

Recognizing the ecological value of healthy montane stream systems has prompted considerable efforts in understanding and mitigating degraded watercourses in the United States (U.S. Environmental Protection Agency and U.S. Department of Agriculture, 1998). In the Sierra Nevada of California, montane meadow systems represent an important link between surface water processes and diverse land use providing many ecological and economic benefits to local natural systems.

Hydrologically functional meadows tend to support root masses that stabilize stream banks against erosion; dissipate stream energy from high flows which reduce erosion, capture bed load that aids in floodplain development and improved water quality and; enhance floodwater retention and groundwater recharge (Ponce and Lindquist 1990, Lindquist and Wilcox 2000, Wilcox, 2009).

Historic land-use practices beginning with 17th century Spaniard livestock grazing and continuing through to the 20th century contributed substantially to the degradation of many montane meadow systems in the Sierra Nevada (Ratliff, 1985). Unregulated early land use practices such has grazing of sheep and cattle, mining practices during the gold rush and accelerated logging practices has resulted in meadow drainage systems that have incised deeply into their floodplains (SNEP, 1996). The seepage of groundwater from incised stream channels lowers water tables across these meadows which negatively impacts the ecological balance between riparian vegetation, animals and aquatic biota. Ultimately these conditions produce meadow systems that are disconnected from their floodplains and substantially reduce watershed services normally provided by healthy meadows.

Although it is assumed that healthy meadow systems store much groundwater, little effort has been focused on measuring the volume of groundwater stored or changes to this volume throughout the water year in Sierra Nevada meadow systems. In an effort to quantify the effects of stream restoration in Bear Creek Meadow in northern California, Hammersmark et al., (2008) determined that successful restoration efforts in the meadow brought several notable benefits including increased groundwater levels and volume of subsurface storage; increased frequency/duration of floodplain inundation and decreased magnitude of flood peaks; and decreased annual runoff and duration of base flow. Further south in the Feather River Basin, Kavvas et al. (2005) estimated the effects of restoration activities on water balance and water quality utilizing large scale regional values to estimate quantitative conditions in the Last Chance watershed. They concluded that restoring degraded meadows will store more water during wet periods, increase base flows during dry periods and increase groundwater storage in general throughout the year. Recent efforts by Loheide et al. (2009) across the Sierra Nevada and southern Cascade ranges have assessed the water requirements for vegetation in wet meadows, concluding that the water needs varied throughout the region as a function of the underlying soil texture (which influenced capillary action) and the elevation-controlled difference in climate (affecting plant phenology).

Groundwater recharge to meadows is partly a function of the storage capacity of the meadow which in turn regulates the rate of groundwater discharge to a stream’s base flow and helps to maintain stream flow during drier periods (Loheide and Gorelick, 2006). Estimates of groundwater storage and flux conditions in montane meadows is predicated on determining the three dimensional configuration (surface area and depth) of meadow sediments and the potential of these sediments to store and release water. This paper outlines our efforts to quantify the volume of groundwater stored in a small montane meadow system and assess the impact of restoration on water volumes throughout the seasons.

## STUDY AREA SETTING AND RESTORATION ACTIVITY

Clarks Meadows is a small (135 acres in area) montane meadow located in the upper Feather River watershed in northern California (Figure 1). The meadow represents the lowest reach of the 48 $km^2$ Clarks Creek basin which drains into the Last Chance watershed, a sub watershed to the Feather River. The 0.46 $km^2$ meadow is a long sinuous feature almost 2.7 km long and averaging about 170 m wide (75 m across at it’s thinnest section to about 280 m wide at it broadest). The gently sloping Meadow (0.01) ranges from an elevation of 1705 m at its northern most point to about 1676 m at its southernmost extent, 2.7 km away. The Meadow’s water sources come from snow melt and groundwater and is drained by one primary perennial stream which traverses through the general center of the meadow though there are several ephemeral streams that enter the meadow during periods of high snow melt and heavy precipitation.

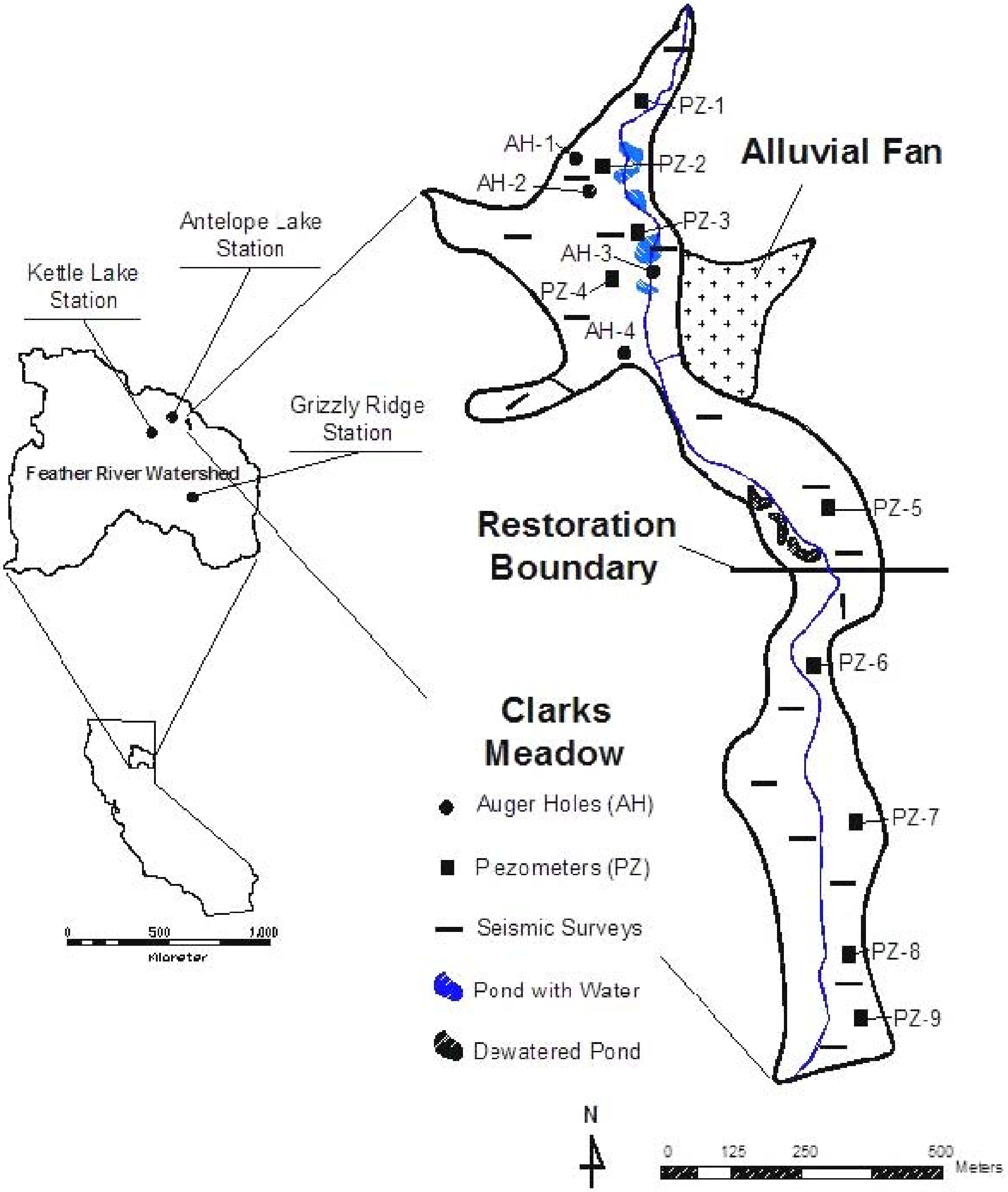


Figure 1. Location of the Clarks Meadow study area. The upper part of the Meadow (above the horizontal line marked Restoration Boundary) has received restoration action while the lower part (below the line) has not. The alluvial fan restricts stream meandering in the narrow neck of the Meadow. Blue shapes (near the alluvial fan) represent ponds with water, black shape (near the restoration boundary) are ponds with no water during summer, 2007). Weather station locations are plotted in Feather River Watershed.

Mean annual precipitation for the region is 695 mm with most of the precipitation (~ 95%) coming throughout the wetter winter months (October through May – Figure 2). The very wet months (December, January and February) yield more than half (~55%) of the water budget for the region. On the other extreme, the months of June, July, August and September receive the lowest volume of rainfall (< 5%) with sporadic and rare summer storms contributing minutely to the overall annual means.

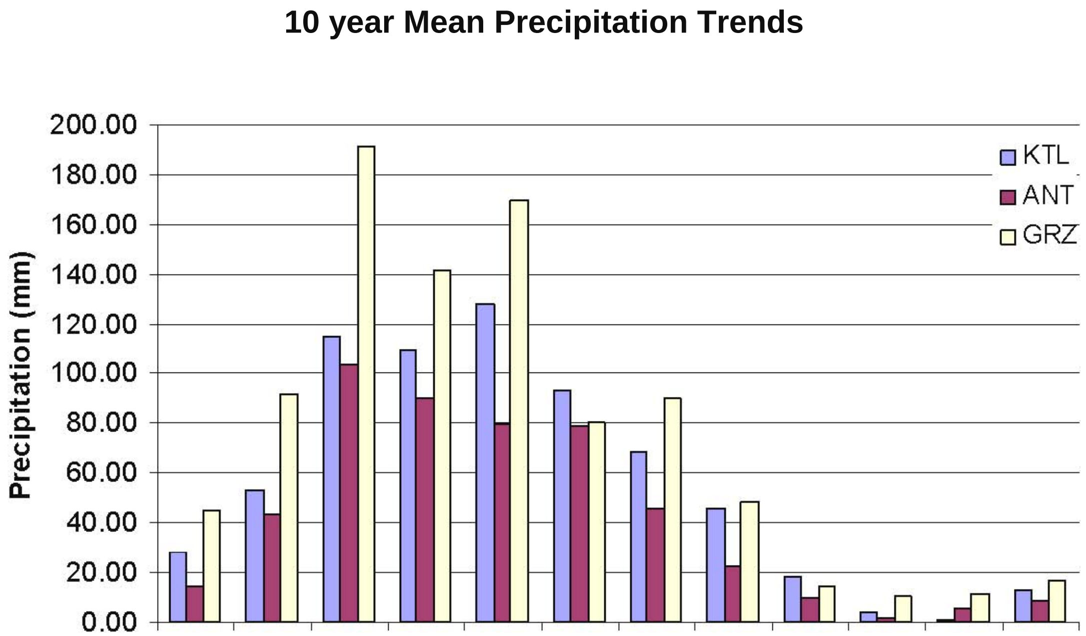


Figure 2. Precipitation trends in the Clark's Meadow region. Data shows monthly mean precipitation rates spanning water years 2000 to 2009 at **Kettle Rock** (KTL), Antelope Lake (ANT) and Grizzly Ridge (GRZ) weather stations (station locations plotted on Figure 1).

The unconsolidated sediments that have been deposited along the modern drainage of Clarks Creek are Holocene and Pleistocene age alluvium (Saucedo & Wagner, 1990). The Meadow is surrounded on three sides by large ridges of Miocene age indurated andesitic pyroclastic deposits of the Diamond Mountains which are capped by the Miocene age Lovejoy Basalt (Durell, 1987, Lydon, 1960 and Saucedo & Wagner, 1990). Where erosion has cut through these volcanic rocks, Cretaceous age hornblende-biotite granodiorites are exposed (Saucedo & Wagner, 1990 and Wagner and Saucedo, 1990). The granodiorite outcrops in various places throughout the meadow and can be seen at the bottom of stream incision sites suggesting that this most likely unconformably underlies the Holocene and Pleistocene age Meadow sediment.

Clarks Meadow was evaluated for restoration work by the Feather River Coordinated Resource Management Group (FRCRM - an alliance of natural resource management agencies, local land owners, private interests, and the public focusing on restoration efforts in parts of the Feather River) in the 1990’s when it was determined that Clarks Creek was disconnected from its historic functional floodplain by incision and degradation of the stream channel.  The cause of this condition is speculative but it is likely that overgrazing around the turn of the 20th century induced stream capture by cattle trails on the floodplain (Feather River Coordinated Resource Management Group, 2001).

Initial restoration efforts showed some success, but frequent floods (‘93,’95, and ’97) and the resulting sediment loads caused additional problems.  The entrenching channel caused dewatering of the meadow and a resulting vegetative conversion from perennial moist meadow grasses and forbs to less desirable dry site annuals and forbs (Feather River Coordinated Resource Management Group, 2001).

Renewed restoration efforts in the upper Clarks Meadow were initiated in late July of 2001 and completed in August, 2001. The existing channel was returned to its original grade (a 1070 m gully was filled in) using pond and plug techniques and the stream was returned to remnant channels on the meadow surface reconnecting it with 50 acres of its natural floodplain (Feather River Coordinated Resource Management Group - Prop 204, 2001). The pond and plug approach involved diverting the flow from the existing incised channel and re-routing the flow to some of the remnant, shallow channels on the Meadow’s surface. Portions of the dewatered eroded channel were then “plugged” with materials excavated from other parts of the Meadow (that produced “ponds”). Over 23,000 cubic yards of materials were relocated in this manner resulting in the creation of ten ponds across the upper Meadow (Feather River Coordinated Resource Management Group, 2004). No restoration work has been undertaken in lower 53 acres of Clarks Meadow, yet. (Lower Clarks Meadow is scheduled for restoration in 2012).

Groundwater measurements taken pre- and post- restoration in Clarks Meadow

**Clarks Creek Seasonal Groundwater Change (1998-2006)**

**1653**

Meadow Elevation

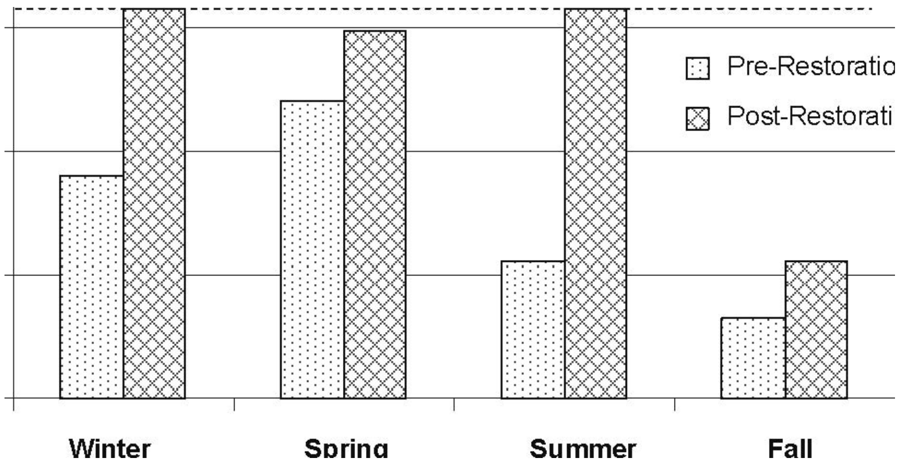
**1652.5**

Pre-Restoration Post-Restoration

**1652**

**1651.5**

**1651**



**Groundwater Elevation (m)**

**Season**

Figure 3. Groundwater flux averaged over 8 years of data collection (from FRCRM, 2010) by FRCRM (Figure 3) show the degree of groundwater storage

improvement throughout an 8 year record (FRCRM, 2001). Substantial groundwater drops are apparent during the Summer and Fall seasons (limited precipitation, little to no recharge and high evaporation rates) under both pre- and post- conditions however, the timing of the groundwater decrease has been significantly altered. Whereas pre-restoration groundwater levels show a general decrease beginning in Spring (presumably as snow melt recharge begins to ebb), post-restoration conditions don’t show that decrease until much later in the Summer to early Fall. Total groundwater changes throughout the year have been reported to be as large as 6 to 7 feet (FRCRM, 2001).

## MEASUREMENTS OF MEADOW SEDIMENT THICKNESS

To calculate the volume of sediments in Clarks Meadow, it was necessary to determine the overall thickness of the subsurface sediments (from the meadow surface to the bedrock below) at multiple locations and then calculate volumes across the surface area of the meadow. We used seismic refraction surveys (a multi-channel, signal-enhanced engineering seismograph (EG&G model 1225)) to collect this subsurface data in part because of its low impact to the study area (it offers a virtually non-destructive method to collect subsurface data instead of driving trucks or drill rigs onto the sensitive meadow surfaces). We strategically measured sediment thickness at 42 different locations throughout the Meadow (Figure 1) based on a location’s proximity to exposed rock near the Meadow margins and predominantly within the Meadow proper (we avoided area where bedrock was exposed or observed to be at or very near the surface). Seismic refraction data does not reveal detailed insight into the physical make-up of subsurface sediments (such as grain-size, subtle stratigraphic conditions, or sediment type) but measures the overall nature of the sediments ability to transmit sound energy. In general, the higher the seismic velocity, the more cohesive and compacted the sediments are. Sharp breaks in seismic velocities (from low velocity to higher velocity) are indicative of a geologic material change, the sharper the seismic break, the more different the geologic materials. When shallow bedrock is encountered, the compacted and consolidated material generates a substantial contrast in seismic velocities relative to the overlying unconsolidated and weakly compacted sediments. It is this contrast and the spacing of the data-collecting geophones that allow for depth calculations to be made (Sharma, 1997 and Reynolds, 1997).

Table 1 outlines the summary results from the 42 surveys. In general, velocity conditions in meadow sediments averaged about 387 m/s which are consistent for unconsolidated, weakly compacted alluvial sediments. Bedrock velocities showed substantial contrasting velocities averaging about 2355 m/s consistent for well consolidated, cemented geologic materials. Table 1. Mean (n=42) summary results of Clark's Meadow seismic surveys.

**Layer 1 mean Layer 2 mean Minimum Maximum velocities (m/s) velocities (m/s) thickness (m) thickness (m)**

387 2355 1.5 5.5

Depth to bedrock data was extrapolated from the seismic data combined with survey UTM coordinates and plotted in GIS to produce a map layer of bedrock elevation. The overall thickness of the Meadow's subsurface sediments ranges from a maximum depth of about 5.5 m in several locations along the longitudinal center of the meadow to less than 1 m in other peripheral sections of the meadow. Figure 4 illustrates the relative depths to bedrock (expressed as meadow sediment thickness) in Clarks Meadow. Several cross-sectional sections are also shown in this Figure and outline the variable nature of meadow thickness throughout the Meadow. Where the Meadow is constricted by alluvial fan sediments to the east and exposed bedrock to the west (near AH-4, Figure 1 and just below cross-section A in

Figure 4) the flow of surface and subsurface waters appears to be confined through a relatively narrow transit. This restriction point likely influences the passage of surface and subsurface waters to the lower Meadow.

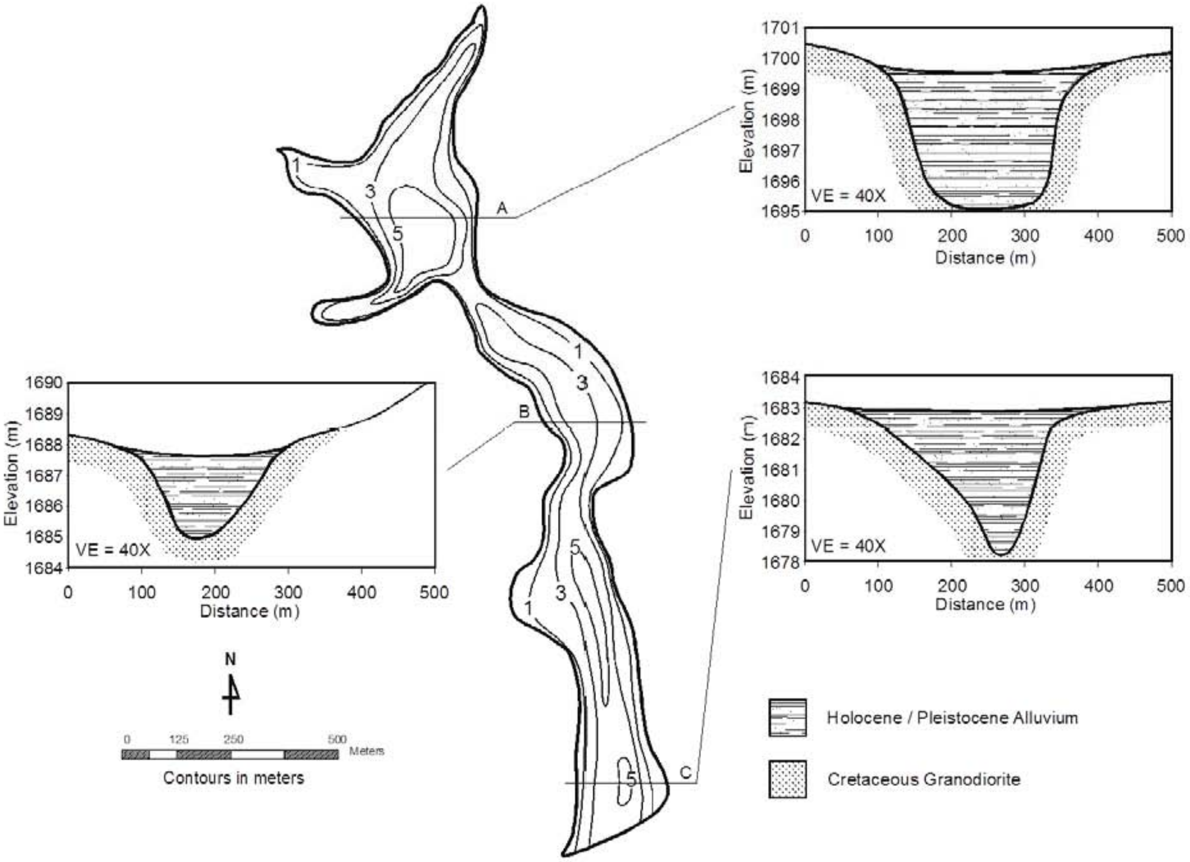


Figure 4. Isopach map of Meadow thickness and cross-sectional areas through the upper, middle and lower part of the Meadow.

The bedrock elevation data was imported into GIS software and then contrasted against ground surface elevation data (collected fromTOTAL Station surveys and USGS DEM datasets) to produce a layer reflecting the thickness and volume of Meadow sediments throughout the study meadow. We used these data layers to extrapolate groundwater volumes under different dewatering scenarios.

## PIEZOMETERS AND GROUNDWATER

Several (9) piezometers were installed throughout Clarks Meadow over the course of this study. Five piezometers were installed in the restored part of the Meadow and four in the lower un-restored Meadow. Figure 1 shows the locations of the piezometers across the Meadow area. Piezometers were constructed with 1 inch diameter metal pipe with several small holes drilled through the casing to allow water to enter the pipe. The pipe ends were capped and the pipe was driven into the ground using a 10 pound slide hammer. In locations where we hand augured boreholes, slotted plastic PVC pipe was inserted into the boring opening and backfilled with augured cuttings. Groundwater data collected from these piezometers were used to measure groundwater flux conditions throughout the study timeline.

Previous efforts to evaluate groundwater levels in Clarks Meadow pre- and post restoration were carried out by the Plumas Corporation. Pre-restoration data (FRCRM Group, 2004) shows that during the peak recharge season (March and April, 2000) groundwater levels in several piezometers across the Meadow were within about 0.3 m of the surface. By early June, those levels had dropped by over 2 meters. Post-restoration monitoring showed that groundwater recharge occurred earlier (by November) and remained at a high level until early July before levels fell about 2 meters. This data suggests that meadow sediments recharge earlier and retain more groundwater for longer periods of time under hydrologically functional conditions.

## MEADOW SEDIMENT PROPERTIES

Hand augured boreholes were advanced in select locations (Figure 1) to verify the thickness of subsurface sediments determined through seismic surveys, delineate the geologic nature of subsurface sediments, collect samples for laboratory analysis, measure groundwater depths, and to conduct field hydraulic conductivity measurements. Subsurface samples collected from the boreholes were analyzed for hydraulic and physical properties (notably grain size). We measured hydraulic conductivity and overall porosity conditions (following ASTM D 5084-90, 1990) as well as in-situ conductivity tests in select borings (following van Beers, 1983) to measure in-place hydraulic conductivity. Table 2 shows the summary results of hydraulic measurements. Table 2. Porosity and hydraulic conductivity (K) summary measurements. Undisturbed data represent laboratory measurements of retrieved samples while In-Situ measurements represent field measurements. AH refers to the auger hole number that the test was conducted in.

|  | **Min Undisturbed** | **Max** | **Min In-Situ** | **Max In-Situ** |
|---|---|---|---|---|
| **Mean Porosity (n=8)** | **K Values (cm/day) (n=9)** | **Undisturbed K Values (cm/day) (n=9)** | **K Values (m/day) (AH-2)** | **K Values (m/day) (AH-4)** |
| **34.95** | **0.03** | **36.3** | **47.7** | **313.5** |

The porosity in unconsolidated meadow sediments ranges from a little over 41% (maximum) to a minimum of about 26.6% yielding a mean porosity (n=8) of almost 35%. These porosity values seem to be consistent for porosities that might be found in sands and silts (up to 50% - Fetter, 1994). The porosity values represent the volume of water that is potentially stored within the pores and voids of the subsurface materials. This value is different than the actual amount of water that might be recoverable from these voids (effective porosity). Effective porosity is a measure of the volume of pore space that will drain in a reasonable period of time under the influence of gravity. Effective porosity is always less than porosity (and in the case of clays, often much less). Early work (Hudak, 1994) suggests that for unconsolidated sands and silts, effective porosity is close to actual porosity (90 to 94%). Good aquifers will tend to have values of effective porosities in the 70% to 90% range although examples of higher and lower values can be found.

It’s important to note that fine-grained sediments (silts and clays) generally have higher porosities than do coarse grained sediments (sands and gravels) and auger sampling of subsurface materials is most effective in finer grained sediments as the clays offer more cohesion to the sample and it is more easily retrievable from the drilling effort. Consequently, the values report here may be slightly skewed to the higher porosities found in finer grained sediments.

Hydraulic conductivity values for collected undisturbed soil samples and in-situ conditions are also outlined in Table 2. Hydraulic conductivity values range from a low of less than 0.03 cm/day in silty sands and gravel at a depth of about 0.5 m in borehole AH-4 to a maximum hydraulic conductivity of about 36 cm/day at a depth of about 0.6 m also in borehole AH-4. The close proximity of both the maximum and minimum conductivity value in the same borehole (within 10 cm of each other) is likely a result of the depositional character of meadow sediments. Frequent over bank flow from spring snow melt and high precipitation events can produce substantial variations in sediment sizes and depositional patterns over very short distances. Pedogenic processes can further influence hydraulic properties as clay production and weathering products inconsistently accumulate in these sediments. Considering the primary source for meadow sediment is generally over bank flood deposits, substantial variations in sediment deposition and ultimately hydraulic conductivity is typical and expected.

In-situ hydraulic conductivity tests are also outlined in Table 2. Values from these tests are noticeably larger than values from the laboratory tests. In-situ tests were conducted across the range of exposed sediment within a borehole and consequently the most conductive zones drive the results. What the data does not indicate however, is how connected these high conductivity zones are throughout the Meadow. Considering the nature of the sedimentation process in meadows (primarily over bank deposition which is strongly dependent on discharge conditions), the continuity of the high conductivity zones is expected to be marginal at best. Drilling logs from the hand augured boreholes shows the stratigraphic arrangement of sediment underlying Clark's Meadow (Figure 5) in the upper part of the Meadow. Surface sediments tend to be organic rich and predominantly silt and clay and are likely the result of ongoing pedogenesis and occasional over bank flooding. The thickness of these sediments varies from about 0.5 m to slightly over 1 m thick throughout the different borings. Groundwater was encountered in AH-1 within this shallow sediment.

Below the upper silt and clays the sediment becomes coarser, grading to a silty sand in AH-1 and AH-2, a fine to coarse sand in boring AH-3, and a sand and gravel in AH-4. Groundwater was encountered in this coarser material in AH-2 and AH-3. With depth, material continues to be of a coarser grain nature than the overlying surface sediments. In two borings (AH-3 and AH-4) a thin silty clay seam is encountered at depth (about 1 m in AH-3 and 1.5 m in AH-4) and separates coarse materials. The extent of this silty clay seam is unknown. Groundwater occurs in this fine grained seam in AH-4.

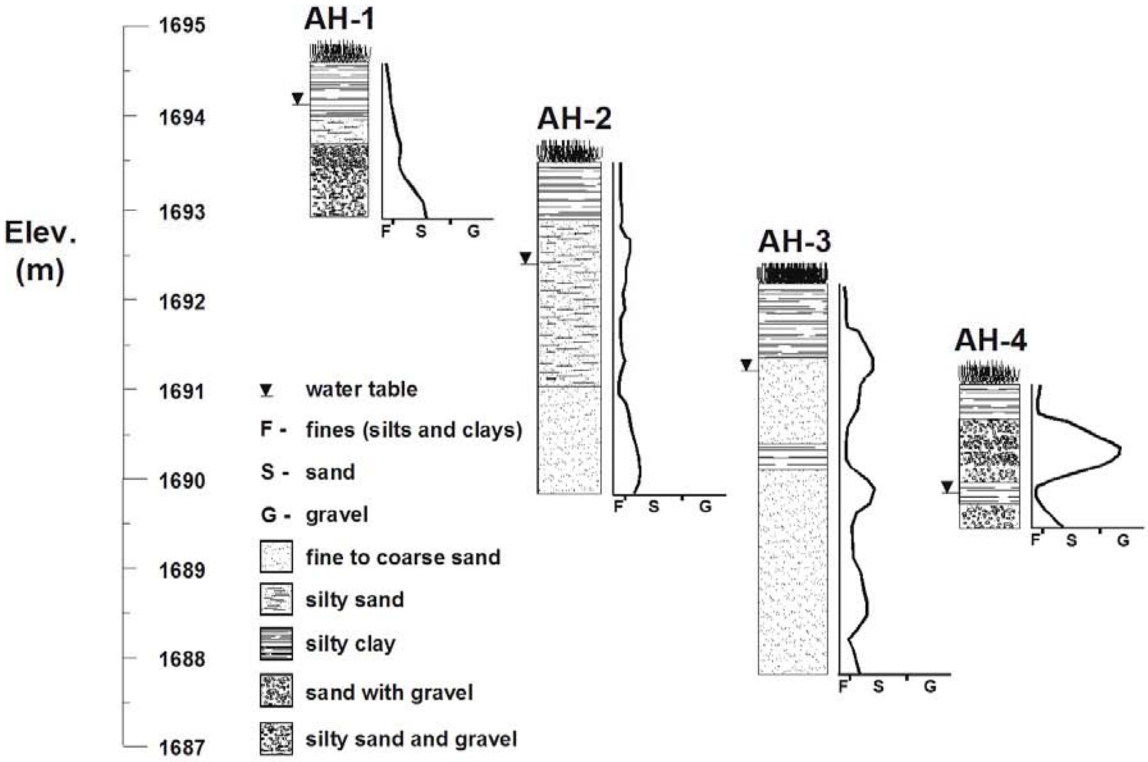


Figure 5. Borehole data from the 4 hand augerings conducted at Clark's Meadow. Grain size data is plotted on the right side of the stratigraphic section and in general shows a coarsening with depth.

## DISCUSSION

The stream channel in the upper restored part of the Meadow is characterized by a small (~ 0.5 m deep and less than 3 m wide) and broad v-shaped channel that frequently overflows and slowly drains overflow waters through sedge grasses and small willow trees along the waterway. In order for discharge conditions to breach the channel banks and flow over bank, a water depth of about 0.5 m is required. In the lower, un-restored part of the Meadow where the stream has substantially incised and widened its banks through erosion, the channel expands to almost 40 m wide in some places and flows through this reach of the channel must reach a depth of over 3.5 m before over bank flow can occur. Sedge grasses are not present here. The

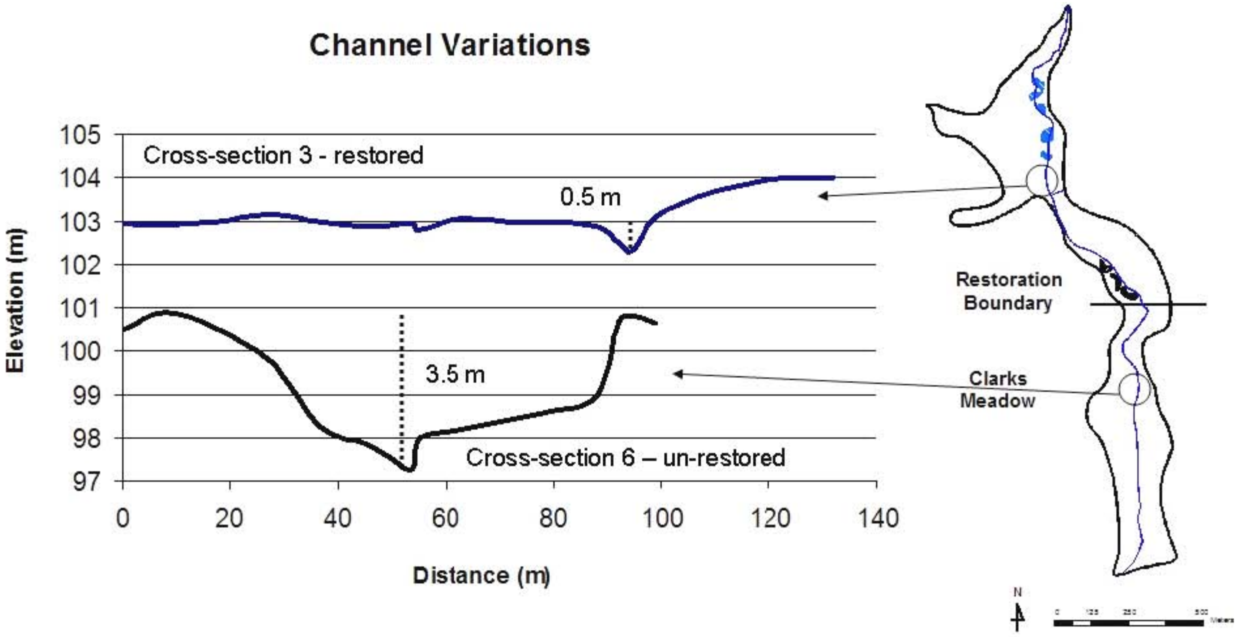


Figure 6. Cross-sectional views of the stream channel through Clark's Meadow. X-Sec 3 illustrates a narrow and shallow channel in the northern restored section of the Meadow, while X-Sec 6 shows a much wider and deeper channel in the southern un-restored part of Clark's Meadow.

incision of the stream channel in this part of the Meadow has enhanced meadow aquifer

dewatering as erosion has cut down into deeper water-bearing sediments that generally have higher hydraulic conductivity than surface soils. This has resulted in the overall lowering of the water table in this part of the meadow. During late summer - early fall (dry season) at least 2.5 m of the sediments exposed in the incised stream channel were dry. The lowering of the water table due to stream incision translates up-meadow as well and likely dewaters sediments somewhat removed from the parts of the meadow actually undergoing channel erosion and incision. Figure 6 illustrates the difference in channel cross-sections between the upper, restored part of the meadow (X-Section 3) and lower, un-restored part of the meadow (X-Section 6). Even though more than 3 m of the meadow stratigraphy was exposed in the X-section 6, little seeping groundwater was observed.

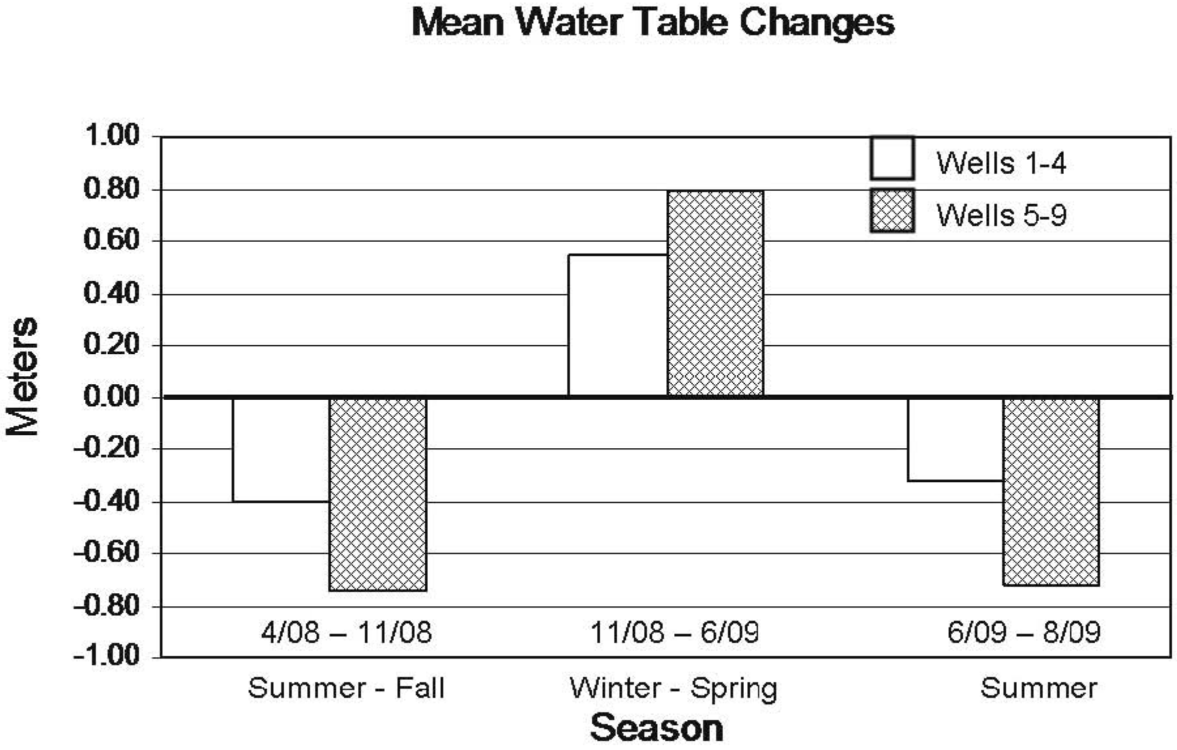


Figure 7. Mean water table changes throughout two dry seasons (4/08 to 11/08 and 6/09 to 8/09) and one wet season (11/08 to 6/09).

Groundwater data outlined in Figure 7 suggests that water table conditions in the restored part of the meadow respond with less variability to seasonal climatic changes than water table levels in the un-restored part of the meadow.  We grouped piezometer data from the restored section of the Meadow (piezometers 1 through 4) and the unrestored section (6 through 9) and measured groundwater levels throughout the recharge (winter to early summer) and depletion (early - mid summer to late fall) seasons. Piezometer 5 is technically located in the restored section but its close proximity to the restoration boundary (within 200 m) and below the narrowing of the Meadow causes groundwater levels to be susceptible to the effect of dewatering from channel incision.  Several of the ponds in the lower part of the restored meadow (produced by the restoration effort) had no water in them during late Summer in 2007 and 2008 suggesting that dewatering of the meadow aquifer had translated this far up stream as well. Consequently, we included piezometer 5 in the un-restored group as data from that well seems to behave similar to other piezometers in the un-restored group.

During the dry seasons, groundwater levels in all piezometers decreased (lost water) due to subsurface recharge to streamflow and aquifers, higher evapo-transpiration rates and little to no recharge. Piezometers located in the restored part of the meadow (1 - 4) show less water table decline during the dry season than do piezometers in the un-restored group. Piezometers in the unrestored part (5 - 9) show much more decline than those in the restored section caused in part by evapo-transpiration and limited recharge but also by dewatering from channel incision. Over the 6/09 to 8/09 dry season, groundwater levels in the un-restored meadow piezometers decreased as much as 120% more than groundwater levels in the restored meadow piezometers.

During the wet season (11/08 to 6/09) groundwater levels in all piezometers recovered but greater groundwater recharge (up to 45%) was experienced in piezometers located in the un-restored part of the Meadow than in piezometers in the restored part presumably because of their greater deficit beginning the recharge season. Where groundwater levels may vary by as much as about 1 m in the restored section, levels may vary as much as 1.5 to 1.6 m in the un-restored section. Even though more groundwater recharges into the un-restored part of this Meadow during the wet season, more water is also lost in this part of the Meadow due to dewatering during the dry season resulting in a more substantial swing in water table levels throughout the year.

We used data from the seismic profiles, borehole logs and groundwater observations to construct three-dimensional models of the Clarks Meadow subsurface in order to calculate groundwater volumes under various scenarios (Table 3). Volume calculations for the entire Meadow (Meadow Sediment Volume in Table 3) suggests that about 1,041,391 $m^3$ of sediment exists between the underlying bedrock and the topographic surface with most of that volume (about 61%) occurring in the restored part of the Meadow. When that volume is multiplied by the mean porosity of sampled sediments (0.35) and adjusted for effective porosity (about 92% of actual porosity), a void volume of about 335,328 $m^3$ is produced (Groundwater Volume in Table 3). Groundwater Volume represents the amount of groundwater stored and available for biological and hydrological services if all of the pores in the meadow were fully saturated with water. Although this condition may occur during prolonged high precipitation events or seasonal snow melt, it represents a short term and infrequent condition.

Table 3 Volume calculations of meadow sediments under different saturation scenarios.

All values in cubic meters.

| | **Restored Section** | **Un-Restored Section** | **Total Meadow** |
|---|---|---|---|
| **Meadow Sediment Volume** | 638,106 | 403,285 | 1,041,391 |
| **Groundwater Volume *** | 205,470 | 129,856 | 335,328 |
| **Peak Seasonal Flux (~1 m)** | 146,200 | 94,460 | 240,660 |
| **Peak Seasonal Flux (~2 m)** | 86,930 | 52,346 | 139,276 |

* – fully saturated

Groundwater levels measured in boreholes and piezometers in the restored part of the Meadow show that over the course of the water year, groundwater levels fluctuate about a meter from peak levels during the late Spring – early Summer (when snow melt and ground saturation are greatest) to lows by Fall – early Winter (after prolonged dewatering with little to no recharge). Extrapolating a one meter decrease in groundwater levels throughout Clarks

Meadow (Peak Seasonal Flux (~1 m) yields a groundwater volume of 240,660 $m^3$ (about a 29% change in water volume from complete saturation). This suggests that under relatively normal seasonal variations, stored groundwater volumes in a hydrologically functional meadow (experiencing no incision or other channel erosion) can decrease by almost 30%. Considering that only under unusual climatic conditions would the entire meadow be completely (100%) saturated, this is probably on the high side.

Under the degraded channel conditions characteristic of the un-restored part of the Meadow, groundwater fluctuates more substantially (almost 2 meters) throughout the water year than in the restored part of the Meadow. If the entirety of Clarks Meadow were to behave as the un-restored part does (as it likely did prior to restoration of the upper part of the Meadow), substantial groundwater loss would occur throughout the water year ultimately yielding a groundwater volume of only about 139,276 $m^3$ (Peak Seasonal Flux (~2 m) – Table 3). This 2 m drop in water level represents a loss of almost 60% of the groundwater stored in the meadow under peak (full saturation) conditions and a 30% loss beyond normal groundwater flux conditions. Considering that Clarks Meadow is partially restored, the restoration effort equates out to a savings of about 59,200 $m^3$ of groundwater volume or about 82% of normal (1 m seasonal flux) storage. The remaining 18% loss (42,100 $m^3$) then comes out of the un-restored lower section and indicates the volume of groundwater that could be added to this budget if it too, was restored.

## CONCLUSIONS

Restoration activities in Clarks Meadow have had a significant effect on groundwater storage conditions. During the dry season, groundwater levels naturally drop due to dewatering but in the restored upper part of the Meadow draw down was noticeably less than in the un-restored part of the Meadow. During the wet season, recharge was documented in all segments of the Meadow but recharge conditions were more extreme in the un-restored lower part of the Meadow. This results in a wider range of groundwater flux throughout the year in the un-restored part of the Meadow and places more stress on vegetation to adjust to these wilder swings in groundwater levels. Substantial volume losses are also documented in the un-restored parts of the Meadow throughout the year which reduces the Meadow’s ability to provide even minimal flows in the channel during the dry season.

The degree of groundwater fluctuation measured in Clarks Meadow has consequences to the flora and fauna that typically inhabit meadows as well as the watershed services the Meadows provide. Lower groundwater levels reduce the quantity of water that slowly seeps into the channel during the dry season which consequently affects the amount of water in the channel and its overall temperature as groundwater is generally cooler than surface water sources. Cooler waters produce more diverse habitat within the stream and along the banks of the channel. Biological succession across the Meadow becomes evident (as witnessed in the un-restored part of Clarks Meadow) as a generally lower water table tends to favor more sage growth than the sedges and grasses that are found in the restored part of the Meadow under a higher water table. More sedge and grass growth along the channel better anchors sediment within the stream channel and reduces the sediment load of the stream ultimately improving water quality downstream. This further inhibits channel erosion during higher flows and retains Meadow sediments in the banks and on the floodplain which tend to further stabilize channel and floodplain conditions.

Although enhanced groundwater storage doesn’t necessarily equate to a change in the overall water budget for downstream users, it does change the timing of waters arriving to downstream reservoirs and users. Over bank flow in meadows force discharge waters to course through meadow / floodplain vegetation which slows the passage of discharge waters promoting infiltration, reducing erosional power and spreading out the discharge peak which in turn reduces peak discharge volumes.

## REFERENCES

ASTM D 5084-90, 1990. Standard Test Method for Measurements of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter, Annual Book of ASTM Standards, Vol. 04.08.

Durrell C., (1987). Geologic history of the Feather River Country, California. University of California Press, Berkely, CA

Feather River Coordinated Resource Management Group, 2004. Clarks Creek Stream/Meadow Restoration Project Fish and Wildlife Monitoring Report. Ca. Dept. of Water Res., District Report. Accessed February 2010 at http://www.feather-river-crm.org/images/pdfs/clarks_report.pdf.

Feather River Coordinated Resources Management (2004) In: Last Chance Watershed Restoration Project CalFed Agreement #no. 2000-EO1 final report. Accessed January 2010 at http://www.feather-river-crm.org/projects/lastchance/Calfed FinalReport MainBody.pdf.

Feather River Coordinated Resource Management Group, 2001. Proposition 204 Final Report (Clarks Creek – Summer, 2001). Accessed, January, 2010 at http://www.feather-river-crm.org/project-files/clarks.pdf.

Feather River Coordinated Resource Management Group, 2004. Clarks Creek Stream/Meadow Restoration Project Fish and Wildlife Monitoring Project. Accessed, January 2010 at http://www.feather-river-crm.org/images /pdfs/clarks_report.pdf

Feather River Coordinated Resource Management Group, 2010. Clarks Creek. Accessed, January 2010 at http://www.feather-river-crm.org/index.php?option=com_content&view=article&id=15&Itemid=14

Fetter, C. W. (1994). *Applied Hydrogeology*, 3rd ed. Upper Saddle River, NJ: Prentice Hall, Inc.

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

Hudak, P.F., 1994. Effective porosity of unconsolidated sand; Estimation and impact on capture zone geometry. Environmental Geology, 24(2), 140-143.

Kavvas, M.L., Chen, Z.Q., Anderson, M., Liang, L., Ohara, N., Wilcox, J., Mink, L., and Benoit, T., 2005. Assessment of the Restoration Activities on Water Balance and Water Quality at Last Chance Creek Watershed Using Watershed Environmental Hydrology (WEHY) Model. Hydrologic Research Laboratory, Civil and Environmental Engineering, UC Davis

Lindquist, D.S. and Wilcox, J., 2000. New concepts for meadow restoration in the northern Sierra Nevada, Feather River coordinated resource management, 2000, accessed October 2009 at http://www.feather-river-crm.org/pdf/ieca.pdf

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

Loheide SP, Gorelick SM (2007) Riparian hydroecology: a coupled model of the observed interactions between groundwater flow and meadow vegetation patterning. Water Resour. Res. 43, W07414, accessed January 2010 at http://www.agu.org/pubs/crossref/2007/2006WR005233.shtml.

Loheide, S.P. and S.M. Gorelick. 2006. Quantifying Stream-Aquifer Interactions through the Analysis of Remotely Sensed Thermographic Profiles and In Situ Temperature Histories. Environmental Science Technology 40: 33363341

Loheide SP, Butler JJ, Gorelick SM (2005) Estimation of groundwater consumption by phreatophytes using diurnal water table fluctuations: a saturated-unsaturated flow assessment. Water Resour. Res. 41(7):1–14.

Lydon P.A., Gay T.E., Jennings C.W. (1960) Geologic map of California: Westwood Sheet. United States Army Corps of Engineers and US Geological Survey, Reston, VA.

Menke, J.W., Davis, C., and Beesley, P., 1996. Rangeland Assessment in Sierra Nevada Ecosystem Final Report to Congress, Vol. 22, Ch. 3, 72 p.

Ponce, V.M. and D. Linquist. 1990. Management of Baseflow Augmentation: A Review. Water Resource Bulletin, American Water Resources Association 26 (2): 254-268.

Ratliff. RD. 1985. Meadows in the Sierra Nevada of California: state of knowledge. Gen. Tech. Rep. PSW-84. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture. 52 pp.

Reynolds, J.M., 1997. An Introduction to Applied Environmental and Environmental Geophysics. New York: John Wiley and Sons

Saucedo, G.L., and Wagner, D.L., 1990, Reconnaissance Geologic Map of Part of the Kettle Rock 15-Minute Quadrangle, Plumas and Lassen Counties, California: California Division of Mines and Geology, DMG Open-File Report 90-7, Scale 1:62,500, 1 Sheet.

Sharma, P.V., 1997. Environmental and Engineering Geophysics. Cambridge University Press, 475 p.

SNEP, 1996. Status of the Sierra Nevada. Sierra Nevada Ecosystem Project Final Report to Congress, Report no. 37–40, SNEP, CERES, Sacramento, CA

U.S. Environmental Protection Agency and U.S. Department of Agriculture. 1998. Clean Water Action Plan: Restoring and Protecting America's Waters. EPA-840-R-98001, National Center for Environmental Publications and Information, Cincinnati, Ohio.

Van BEERS, W.F.J., 1983, The Auger Hole Method, A field measurement of the hydraulic conductivity of soil below the water table, International Institute for Land Reclamation and Improvement.

Wagner, D.L., and Saucedo, G.J., 1990, Reconnaissance Geologic Map of The Milford 15-Minute Quadrangle, Lassen and Plumas Counties, California: California

Wilcox, J.G., 2009. Water Management Implications of Restoring Meso-scale Watershed Features. Accessed February, 2010 at http://www.feather-rivercrm.org/images/pdfs/wm_implications.pdf.