Restoration of geomorphic structure, hydrologic regime, and vegetation in Upper Halstead Meadow

Evan Wolf, MS and David Cooper, PhD
Department of Forest, Rangeland and Watershed Stewardship
Colorado State University, Fort Collins, CO 80523

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Introduction

In September of 2007 Sequoia National Park restored the geomorphic and hydrologic regime of Upper Halstead Meadow (upstream from the Generals Highway) by filling in a large erosion channel. This project was conceived as a pilot project for testing methods and proving the efficacy of large-scale restoration of montane wet meadows, with the goal of eventually restoring the whole meadow including the much larger gully of Lower Halstead Meadow (below the Generals Highway). Livestock intensely grazed Sierra meadows in the late 1800s to early 1900s (Benedict 1982, Rundel et al. 1988, Allen and Bartolome 1989), causing widespread degradation (Ratliff 1985, Odion 1988) of the sort that likely initiated gully formation in Halstead Meadow. Erosion almost certainly accelerated after 1934 when a culverted road was constructed across the meadow, concentrating surface water flow through a fixed location. A series of concrete check dams was built in Lower Halstead at an unknown time prior to 1955 to slow the already-severe erosion. Large flood events in 1955 and 1997 widened and deepened the gully and destroyed parts of the highway and the check dams. Descriptions of Halstead Meadow following the 1955 storm indicate that gully depths were 5 to 6 feet, much of which apparently eroded during that single storm event. By 2005, sections of Halstead Meadow had a gully over 30 feet wide and 18 feet deep, eroded down to bedrock through ~10,000 years (Wood 1975) of accumulated meadow sediment. A study comparing the hydrologic regime and vegetation of Halstead Meadow to nearby meadows in similar geomorphic configurations (Cooper and Wolf 2006) showed that large portions of Halstead had much deeper water tables and different plant communities than comparable, non-gullied meadows. However, soil profiles in Halstead were similar to the reference sites, demonstrating that all the meadows had formed by the accretion of horizontal layers, many of which were highly organic, indicating long periods of perennial soil saturation.

The evidence from Cooper and Wolf (2006) indicated that the erosion gully and upland vegetation found in Halstead Meadow were not part of the natural features of meadows in the area. Historical construction efforts and their qualitative descriptions demonstrated that the erosion was severe, ongoing, and could not be effectively prevented or reversed by a small number of check dams. An additional on-site observation that argued against a restoration design involving dams and ponds was that numerous subterranean burrows were acting as pipes, draining intact wetland areas to lower elevation ponds and gullies. A stepped pond design would necessitate leaving some portion of the restored sloped meadow surface higher in elevation than flat-water pond surfaces. Mountain Beaver (*Aplodontia rufa*) seem to exploit this type of landscape and water table gradient for building burrows, causing drainage of the elevated meadow surface (Figure 1).

Figure 1. Mountain Beaver burrows in Lower Halstead Meadow. Photos are taken from the degraded Lower Halstead (LH) zone looking west towards the Intact Lower Halstead (ILH) zone. In the top panel, surface sheetflow is visible in the background and the burrows at surface are visible as water flow paths surrounded by drained, dry ground. Burrows seen in the top panel drain by subterranean channels to a water filled basin, lower panel.

The initial grazing disturbance had broken down the meadow's natural stabilizing feedback between plants, soil, and water. This feedback consisted of dense vegetation that had held the soil in place, causing surface water entering the meadow to spread out and slow down, creating a sheet flow hydrologic system. When plants were grazed and roots and soil trampled, large flood events that spread across the flat, newly-bare soil were sufficient to trigger erosion and initiate channel formation. Once a channel formed it became a low point in an otherwise very level meadow landscape, concentrating flow and triggering additional erosion and further incision that lowered the adjacent meadow water table. A lower water table favored upland plants, preventing sod-forming wetland plants from reestablishing to stabilize the soil surface. To break the cycle of erosive channelized flow and to reestablish stabilizing vegetation across the site, the entire Upper Halstead Meadow gully was filled with sediment to restore meadow geomorphology by matching fill elevations to the remaining meadow surface. The geomorphic restoration eliminated preferential flow paths and created level topography that has restored the sheet flow hydrologic system. To prevent erosion of the bare sediment, flow must be slowed by surface roughness elements and erosion control blanket for long enough to allow plants to establish and re-form a dense root and rhizome network that will provide self-sustaining, long-term erosion resistance (Micheli and Kirchner 2002).

The goals of the Upper Halstead Pilot Project were to restore the gemorphic structure, hydrologic regime, vegetation and wetland functions in the portion of Halstead Meadow upgradient from the Generals Highway to what existed prior to meadow damage and what is present in the intact portions of Upper and Lower Halstead and at reference sites. The once-wet Upper Halstead Meadow has been severely impacted by the cumulative effects of livestock grazing, road construction, channel development, channel head cutting, water table decline, upland plant invasion, and rodent activity. The specific criteria for the four project goals are as follows:

1. **Geomorphic structure**. A key element of this design is the creation of a meadow surface that is nearly level in cross section. The topography of Halstead Meadow should be flat for the entire meadow width, perpendicular to the direction of water flow. There should be no raised zones, channels, or other landforms including pocket gopher mounds or tunnels that would concentrate flow or prevent sheetflow from occurring across the entire valley width. Logs, placed perpendicular to the flow direction to disperse water flow, were an original part of the geomorphic goal but were found to be problematic, so were removed.

2. **Hydrologic processes**. The primary hydrologic goal is to reestablish a saturated sheet flow system across the entire upper meadow throughout the growing season. This is the hydrologic condition observed in the reference meadows and intact portions of Upper and Lower Halstead Meadow. A specific hydrologic goal would be that the water table at monitoring wells within the

restoration area must be within ±1 standard deviation of the mean water table of wells in the reference meadows. In addition, no channelization of flow or erosion should occur.

3. **Vegetation restoration**. The vegetation goal is to reestablish self perpetuating and rapidly spreading populations of *Scirpus microcarpus, Oxypolis occidentalis* and *Glyceria elata* in the restoration area. Through time other native wetland plants will become established in the restored communities by clonal spread from the wetland margins, or seed dispersal into the wetland, and species diversity will become similar to that found in the reference meadows. Specific goals for the plantings are:

a. a minimum mean of 75% seedling survival after three years, and

b. the density of shoots of species planted in monitoring plots should have a steady increase over time.

4. **Restoration of wetland functions**. The hydrologic and vegetation goals for Halstead Meadow will create conditions that will allow organic matter accumulation in soils. Layers of organic soils can be seen in the meadow stratigraphic section, and occur at the surface in portions of Halstead Meadow today. Most of the meadow will likely not develop organic or peat soils, however where perennially saturated conditions occur the rate of organic matter accumulation will exceed the rate of organic matter decomposition due to water-logging and organic matter will accumulate in the soil. Soil organic matter is critical to the functioning of wetlands by increasing water storage, providing an adequate seed bed for native plants, nutrient sequestration, improved plant production and thus the development of dense vegetation which will disperse and slow the flow of water. The current hydrologic regime does not maintain saturated conditions throughout the meadow, and organic matter cannot accumulate. However, a trend of increasing soil organic matter is an important goal for this project and a positive indication that wetland soil processes have been restored. There should be a long-term trend of increasing organic matter in these soils that would over time match that found in reference meadows.

As of the writing of this report, three of the four goals have been adequately monitored to determine success. The fourth goal of wetland function will not be assessed here because the accumulation of organic matter is a long process and has not yet been monitored for success. This report documents and analyzes the geomorphic, hydrologic and vegetation changes that have occurred at Upper Halstead Meadow as a result of the 2007-2008 restoration project.

Methods

Study sites and treatment zones. Figure 2 shows an aerial view of Halstead Meadow, with the well locations and restoration treatment zones indicated. The Filled Upper Halstead (FUH) zone is the former location of Halstead Creek's erosion gully. All geomorphic restoration occurred in this zone, where gullies were filled with sediment to the level of the surrounding meadow surface. The FUH zone was planted in June 2008 with nursery grown seedlings of *Scirpus microcarpus, Oxypolis occidentalis,* and *Glyceria elata*.

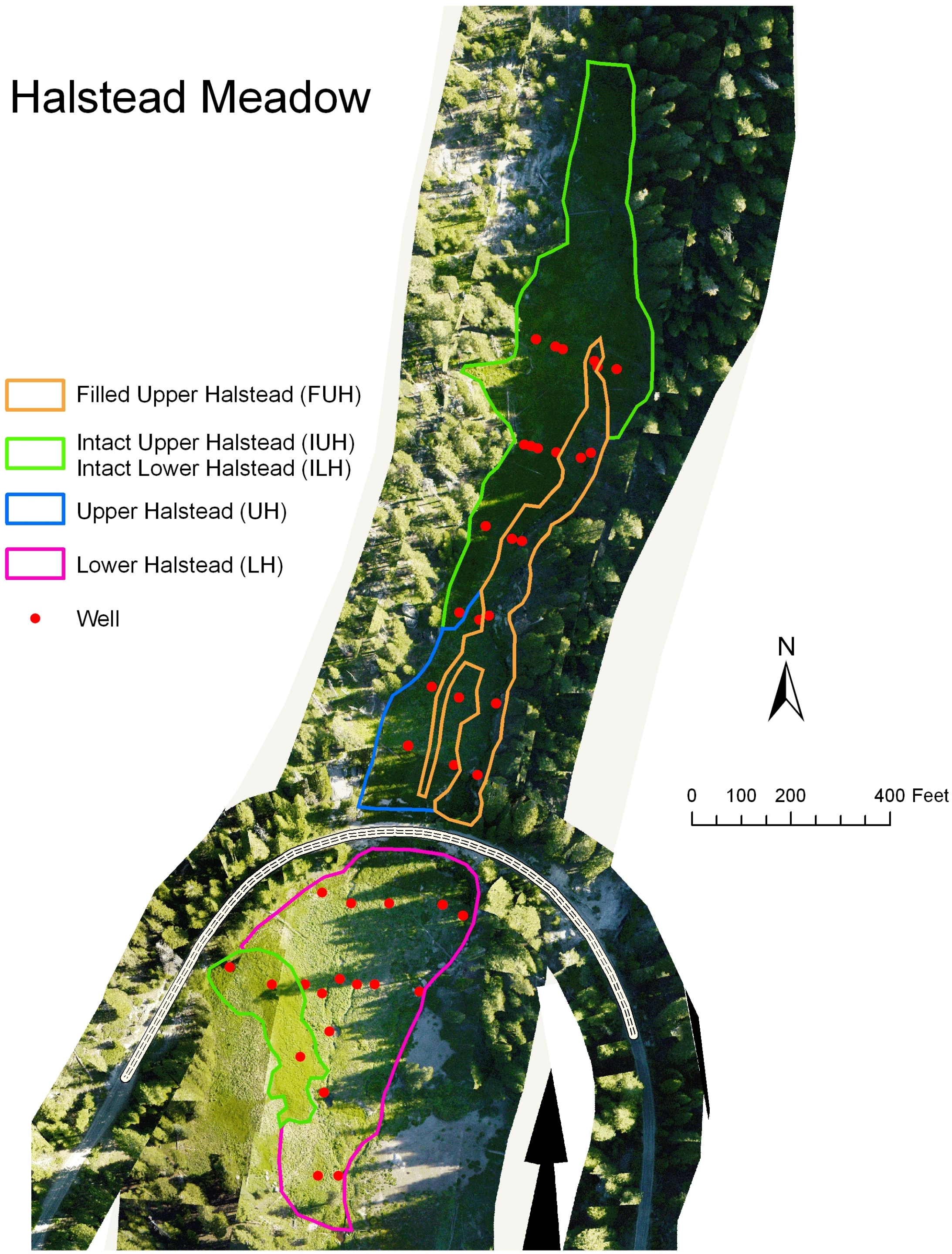

Figure 2. Composite aerial photograph showing Halstead Meadow and the Generals Highway with well locations and treatment zones overlaid. See Methods for a description of each zone.

The Upper Halstead (UH) zone was an upland vegetation area that was outside of the gully and received no fill material in 2007, so the ground surface and soil were not directly altered. However, as a result of the gully filling, the groundwater level rose significantly and the area now receives perennial sheet flow. The vegetation and soil seedbank in UH were unaltered, but a small number of the same three species of seedlings were planted to facilitate the transition to wetland vegetation. The Lower Halstead (LH) zone was unaltered by the restoration in Upper Halstead and still contains a very large erosion gully that conveys a large amount of water and creates deep water tables and upland vegetation on adjacent meadow surfaces. The Intact Upper Halstead (IUH) and Intact Lower Halstead zones (ILH) are areas of perennially saturated soil and sheetflow hydrology with no significant channels, are covered with dense native wetland vegatation, and were unaltered by the restoration.

In order to place Halstead Meadow in a regional context and compare it to similarly situated meadows, five reference sites were selected and instrumented. The five sites are all within 6.5 km and 180 m elevation of Halstead Meadow, and are Upper Cabin, Dorst, Round, Log, and Crescent Meadows. See Cooper and Wolf (2006) for more detail about the reference sites.

Geomorphology. In September of 2007, the erosion gully in Halstead Meadow upstream from the Generals Highway was filled with compacted sediment until the level matched the surface topography of the intact meadow (Figure 3). A total station (TopCon Positioning Systems Inc.) was used to conduct a topographic survey of the ground surface prior to, during, and after the earthwork. In addition, LIDAR data was obtained for Halstead Meadow from the Federal Lands Highway Administration, and together with the survey data, was used to create a three-dimensional model of the meadow surface. The model was used to calculate the amount of volume of material that would be required to fill the gully and restore the level topography of the meadow. Trees were felled and downed logs were placed across the meadow on contour to slow water flow and match the conditions observed at the reference sites, where downed trees play a key role in detaining water flow. The placed fill was intentionally compacted by heavy equipment traffic to create a more cohesive and less erodible soil.

Hydrology. Once the gully was filled, the site hydrologic regime changed dramatically, producing sheet flow across the entire meadow, and raising groundwater levels in the adjacent unfilled meadow. A network of 23 groundwater monitoring wells were installed in Upper Halstead meadow, with another 68 wells installed across Lower Halstead and the five reference meadows. Water levels in the wells were measured by hand periodically throughout the growing season. Hydrologic patterns were analyzed graphically as well as statistically using SigmaPlot and OpenOffice Calc.

Figure 3. Upstream view of Upper Halstead in 2005 (top) before restoration and 2008 (bottom) after restoration. The planted seedlings are visible in rows in the filled gully at right, while the formerly dry meadow and intact meadow vegetation dominate on the left. Note the dry meadow surface adjacent to the 2005 stream-filled gully, while the entire meadow width is covered in thin sheetflow in the 2008 photo following geomorphic and hydrologic restoration.

Vegetation. In Spring of 2008, 53,200 nursery-grown seedlings of *Scirpus microcarpus, Glyceria elata*, and *Oxypolis occidentalis* were delivered to the restoration site. In June 2008 34,250 of these were planted in the Filled Upper Halstead (FUH) zone at a target spacing of 45.7 cm (18 inch), and 15,120 were planted in the formerly dry Upper Halstead (UH) zone at a target spacing of 50.8 cm (20 inch). Of the remaining plants, about 3400 were kept in a greenhouse and planted in problem spots in the summer of 2009, and the other 500 were rejected upon delivery for their poor condition. Planting in offset rows was specified, with plants within a row separated by the desired spacing distance, (18 or 20 inches) and the distance between rows (not between plants across rows) also equal to the same desired spacing distance. This spacing pattern allocates an area to each plant equal to the desired spacing distance squared, 2090 cm^2 (324 in^2) for 45.7 (18 in) spacing, 2581 cm^2 (400 in^2) for 50.8 cm (20 in) spacing. With the plant spacing targets for the FUH zone (45.7 cm, 18 in), an average of 4.78 seedlings should have been planted per square meter, and for the UH zone (50.8 cm, 20 in) an average of 3.88 seedlings per square meter were to be planted. Figure 4 shows the layout of the plantings where X represents the spacing between plants within a row (red solid lines) and the row spacing (blue solid line), and the plant distance between rows is 1.118*X (red dashed lines). The area allotted for each plant is X^2, represented by the black squares in Figure 4, and the number of plants per unit area is $1/X^2$.

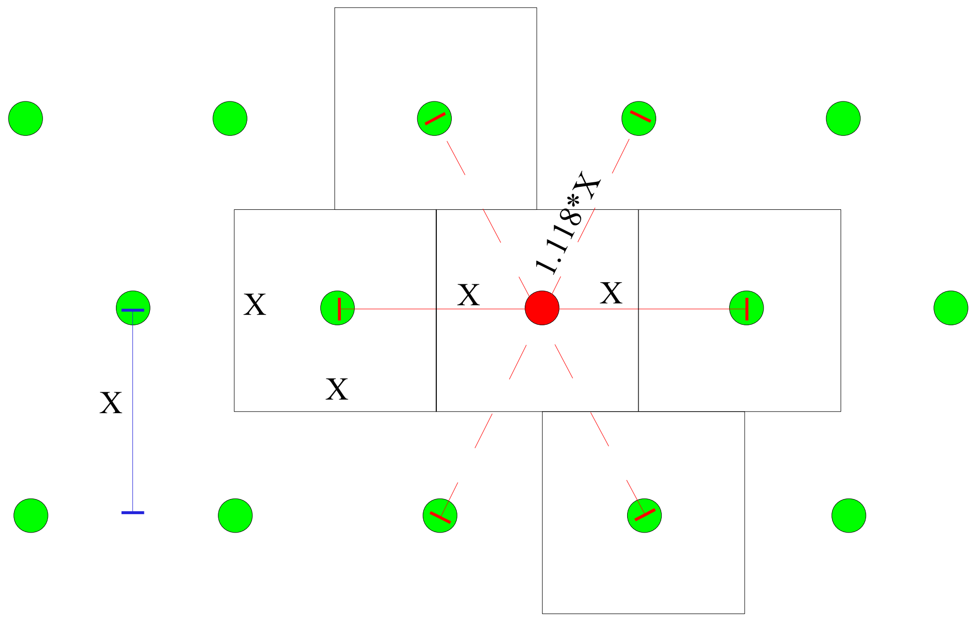

Figure 4. Diagram showing the layout of plants (dots) in offset rows. Each plant is separated from neighbors within its row by the defined spacing distance (red lines), and the neighbors in adjacent rows by 1.118*the defined spacing distance. This layout is easily divided into squares around each plant, with areas of the defined spacing distance squared. The spacing between rows, shown by the blue line, is equal to the defined spacing distance.

In order to assess the quality of the plantings, which are critical to project success, the density and survivorship of the seedlings was determined in September 2008, three months after planting. The number of live and dead seedlings were counted in fifteen 25 m^2 plots distributed throughout the entire planted area of FUH.. From these data planted density and percentage survival were calculated. Also, at each well within and outside of the restoration zone, percent cover of plant species was measured in a 3m-radius circle around each well. The pre-restoration floristic composition of the vegetation was recorded in late summer 2005 for Halstead Meadow and all reference sites, and late summer 2010 for Halstead Meadow. A single observer familiar with the vegetation made an ocular estimate of percent cover by species.

Project damage and repair: On October 14th 2009 a large storm dropped over 20 cm of rain in a 24 hour period and eroded approximately 10% of the sediment from the FUH zone and washed away or deposited sediment on top of almost a third of the seedlings planted in 2008. It was determined that, in the absence of dense vegetation, the long on-contour logs may have exacerbated the erosion by impounding storm water that then cascaded over the top, channeled over a low point, or undercut the logs, concentrating and energizing surface flow. In addition, the shear stress rating of the original erosion control blanket was likely exceeded by the storm flow (Herrera 2010). A repair of the erosion was made in November 2009, the new gully was refilled, and all contour logs were broken up and scattered where practicable.

In addition to issues caused by the logs, it was noticed that transplant growth seemed to be lowest in the FUH areas of highest soil compaction. To test this, 24 random points were selected within the FUH zone and the height and width (the distance between the two most-separated shoots) of the five closest *Scirpus microcarpus* plants were measured in September of 2009, 14 months after transplanting. At each of the 120 plants a soil strength reading (in KPa) was taken with a digital penetrometer (Spectrum Technologies Inc. SC 900). The relationship between plant growth and soil compaction was analyzed with linear regression. Initial results from a companion study investigating the effects of a wood chip amendment on soil compaction indicated that a significant reduction in compaction could be achieved by mixing 70% soil with 30% wood chips, by volume. The fill used for the 2009 storm repair was a mixture in this ratio, and in the spring of 2010, this bare area was replanted with *Scirpus microcarpus* seedlings. The October 2009 storm and associated earthwork during the repair destroyed all but 2 of the monitoring well sites in the FUH zone and, while wells were replaced in the damaged areas, the vegetation data taken in 2010 shows less than one growing season of the newly planted *S. microcarpus* seedlings. Only the two surviving plots in the FUH zone (at wells 96 and 87, see Appendix 2, separate document) record the growth of the 2008 plantings from the original restoration.

Results and Discussion

Geomorphology: A comparison of the pre- and post-restoration surveys, using 3D models and cross-sections (see Cooper and Wolf 2006 for figures), showed that 5,600 cubic meters (7,430 cubic yards) of compacted fill were placed in the Upper Halstead erosion gully. The constructed meadow surface created topography that was level across the entire valley width. All channels were filled except for one small channel that was left on the west, intact, vegetated side. This channel was left in place to keep as much surface flow off of the bare and erodible fill on the east side of the meadow. Once vegetation has become completely established on the fill, it is advised to block this channel to prevent any downcutting, headcutting, or widening.

Hydrology: At the five reference meadows and the intact portions of Upper and Lower Halstead (IUH and ILH), the water level remained within 65 cm of the ground surface throughout the growing season during all 6 years of monitoring (Figure 5). This study period included the very wet year of 2006 followed by the very dry year 2007, and water levels in reference sites were only slightly deeper in the summer of 2007. A comparison of water levels in Upper Halstead (UH) wells prior to and following the September 2007 restoration shows a dramatic ground water rise in all wells following restoration (Upper Halstead panel, Figure 5). Prior to restoration the UH water table was only briefly within 50 cm of the soil surface during the period of annual spring snowmelt in May/June, and was a meter or more deep during mid to late summer. Following restoration, the water table in all wells was within 20 cm of the ground surface for the entire growing season. This indicates that all UH sites transitioned from a non-wetland hydrologic regime prior to restoration, to a wetland hydrologic regime after restoration.

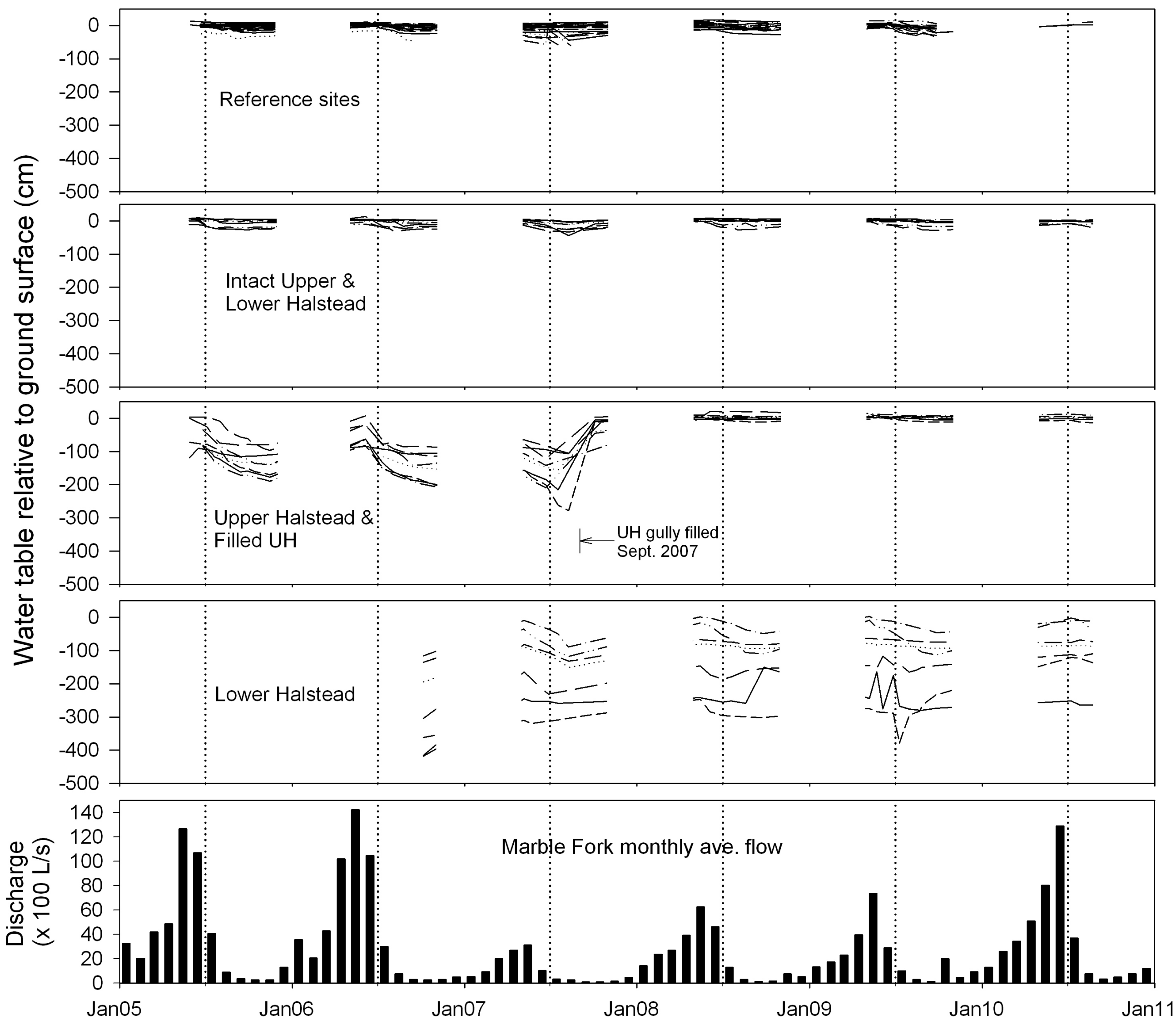

Figure 5. Water table position relative to the ground surface at the reference meadows and sites within Halstead Meadow. Monthly average discharge of the Marble Fork of the Kaweah River is shown as an estimate of relative discharge through Halstead Meadow. Dotted lines are 01 July.

One of the stated hydrologic goals of the restoration (Cooper and Wolf 2006) was to bring the water levels in formerly dry and gullied sections of Upper Halstead (FUH and UH) to within one standard deviation (SD) of the average water level at the reference site and intact portions of Halstead meadow. The average water level of all readings in all years from the reference and intact sites was 3.1 cm below the ground surface, with a standard deviation of 10.1. Therefore the range of water levels within 1 SD of the average reference water level is between 13.2 cm below ground to 7.0 cm above ground. For normally distributed data, 68.2% of the observations fall within 1 SD of the mean. Shapiro-Wilks tests for normality indicated that none of the three data sets, reference sites ($n = 1058$, $W = 0.803$, $p << 0.0001$), restored Upper Halstead ($n = 299$, $W = 0.7312$, $p << 0.0001$), or pre-restroation Upper Halstead ($n = 186$, $W = 0.9825$, $p = 0.02$) were normally distributed. Both the reference and the restored Upper Halstead data sets are significantly skewed to the left, while the pre-restoration Upper Halstead data display significant kurtosis, with a broad, short peak (Figure 6).

Because none of the water level data sets are normally distributed, the proportion of the data falling within one standard deviation of the mean departs from the predicted 68.2%. In the reference sites well data, 13.4% of the readings are deeper than -13.2 cm (mean – 1 SD), and 6.2% are higher than 7.0 cm (mean + 1 SD), for a total of 19.6% of the readings falling further than 1 SD from the mean, or 81.4% of data within 1 SD of the mean. Basic transformations (e.g. log, square root, power) failed to normalize any of the data sets, and the non-normality and unbalanced design (unequal number of measurements for the different data sets) precluded conducting an analysis of variance (ANOVA). However, it is clear from a visual examination of the graphed data, that the restored Upper Halstead data follows a very similar distribution to the reference site data, whereas the pre-restoration Upper Halstead does not. 83.2% of restored Upper Halstead well readings fall within +/- 1 SD of the reference well average, exceeding the 81.4% of the reference data, indicating an even tighter clustering of the restored data near the ground surface zero value. On the other hand, only 3.7% of the pre-restoration

Upper Halstead readings were within 1 SD of the reference average, indicating a completely different hydrologic regime.

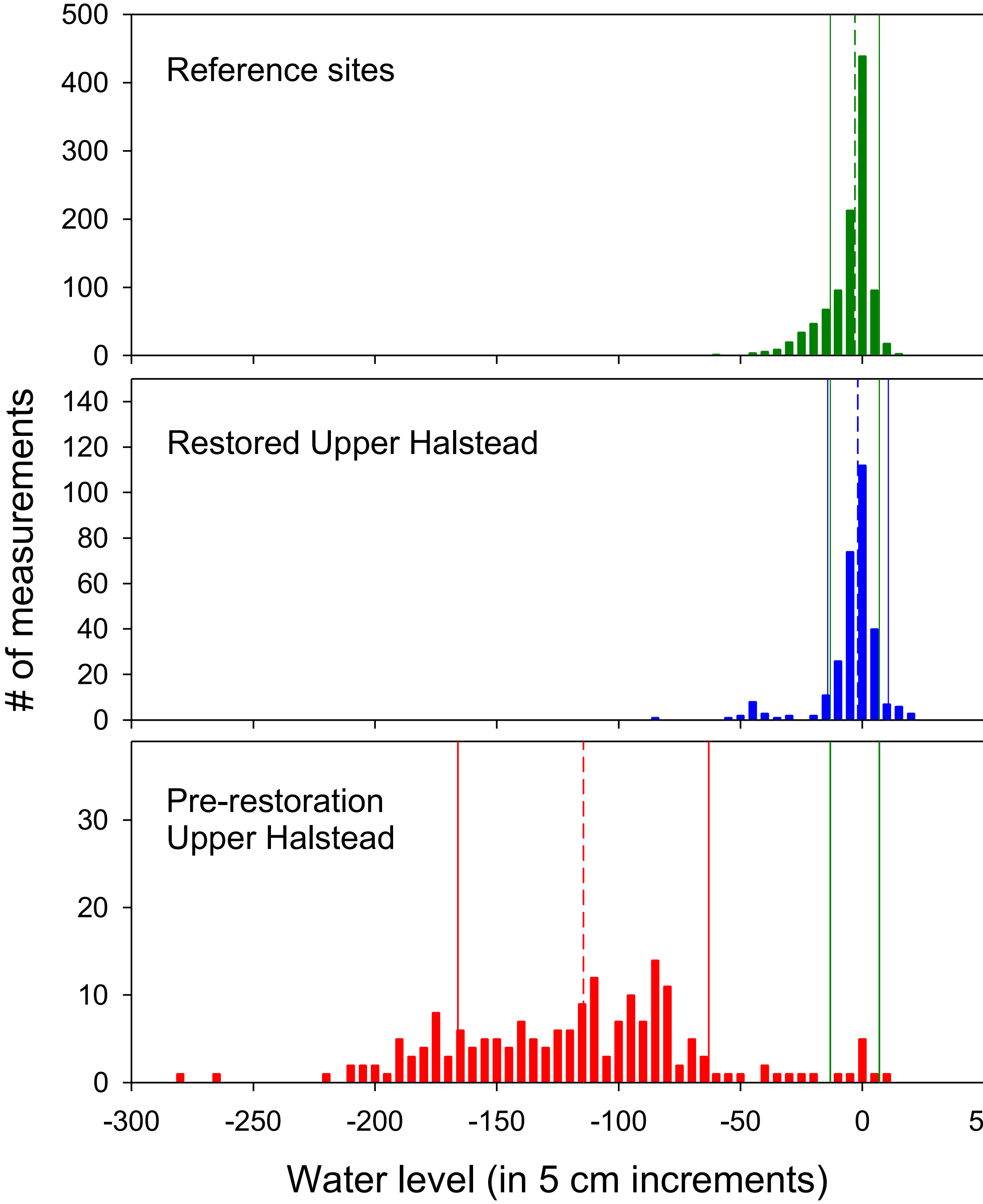

Figure 6. Histograms of the water level readings at the reference sites (green, top), restored Upper Halstead Meadow (zones FUH and UH, blue, middle), and pre-restoration Upper Halstead (zone UH, red, bottom). Average values (dashed vertical lines) +/- 1 SD (solid vertical lines) are shown, with the reference range of +/- 1 SD overlaid (solid green lines) on the other graphs to illustrate degree of overlap in the data. Note the different scales on the y-axes.

Vegetation: Of the 34,250 seedlings that were planted in the FUH zone in June 2008, a sampling of 1740 of them showed that three months later, 96.8% of the transplants were still alive (Table 1). The measured density of all plantings was 4.64 plants per square meter, very similar to the specified 4.78 plants per square meter. The specified planting ratio of 3:1:1 (60%, 20%, 20%), *Scirpus*, to *Glyceria*, to *Oxypolis*, was altered by as much as 6.9%. This shift was partly due to problems the contractor had with growing *Glyceria* and *Oxypolis,* causing disproportionate death of these species after before and possibly after planting. In addition, we observed black bear preferentially grazing on *Oxypolis* seedlings early in the growing season and deer grazing *Scirpus* and *Glyceria* seedlings late in the growing season. No plot in our sample had survival below the stated success criteria of 75%, with the lowest value being 89.5%. No assessment of planting survival or density was made in the UH zone, outside of the FUH zone, due to dense growth of existing plants.

Table 1. The September 2008 sample of seedlings in the FUH zone, showing percent survival and planting density.

plot	*Scirpus microcarpus*	*Glyceria elata*	*Oxypolis occidentalis*	dead	TOTAL	% survival
1	83	12	30	3	128	97.7%
2	87	11	13	9	120	92.5%
3	60	13	36	3	112	97.3%
4	82	7	14	2	105	98.1%
5	80	19	7	1	107	99.1%
6	109	24	3	2	138	98.6%
7	72	19	10	2	103	98.1%
8	77	25	11	0	113	100.0%
9	65	14	6	10	95	89.5%
10	82	29	22	6	139	95.7%
11	79	30	15	4	128	96.9%
12	74	11	28	2	115	98.3%
13	67	34	8	2	111	98.2%
14	70	19	10	10	109	90.8%
15	77	24	16	0	117	100.0%
TOTAL	1164	291	229	56	1740	
% of total	66.9%	16.7%	13.2%	3.2%		96.8%
ave. plants/m^2	3.10	0.78	0.61	0.15	4.64	

In 2005, the vegetation in the Upper Halstead wells was dominated by *Senecio triangularis*, *Heracleum lanatum, Elymus glaucus, Mertensia ciliata*, and *Rumex salicifolius* (see Appendix 2, separate document). Of these, only *R. salicifolius* is an obligate wetland species, according to the National Wetland Inventory. By late summer of 2010, 3 years after restoration, the vegetation in Upper Halstead had changed and was dominated by *Rumex salicifolius*, *Scirpus microcarpus*, *Glyceria elata* and *Juncus ensifolious*. The only dominant species common to the pre- and post-restoration community was *R. salicifolius*, which was the only obligate wetland species dominant in the pre-restoration plant community. The shift in Upper Halstead vegetation composition from 2005 (UH05) to 2010 (UH10) in relation to the vegetation at the 5 reference sites and other Halstead sites, is shown in a Detrended Correspondence Analysis (DCA) ordination plot (Figure 7). Sites with similar vegetation composition are plotted close together in the DCA, and their distances apart along the axes represent the primary difference between sites. The dashed blue arrow in Figure 7 shows that from 2005 to 2010, the vegetation in the formerly upland portions of Upper Halstead (UH05) shifted from being similar to Lower Halstead (LH) plots to being more similar to reference sites (green dots) and intact portions of Upper and Lower Halstead Meadow (IUH, ILH). If extended, the blue vector connecting UH05 to UH10 would nearly intersect the Filled Upper Halstead site (FUH), which is vegetated by the 2008 plantings of *Scirpus microcarpus, Glyceria elata,* and *Oxypolis occidentalis*. The planted vegetation of Filled Upper Halstead plots (FUH) are similar to reference sites and intact portions of Halstead Meadow. However, plant density and total canopy cover in FUH plots are lower than reference sites. Bare ground was not included as a “species” in the ordination because the different potential causes for exposed soil (lack of water or disturbance from restoration earth work) could confound the hydrologic analysis. See Appendix 2 (separate document) for the complete vegetation table including bare ground data.

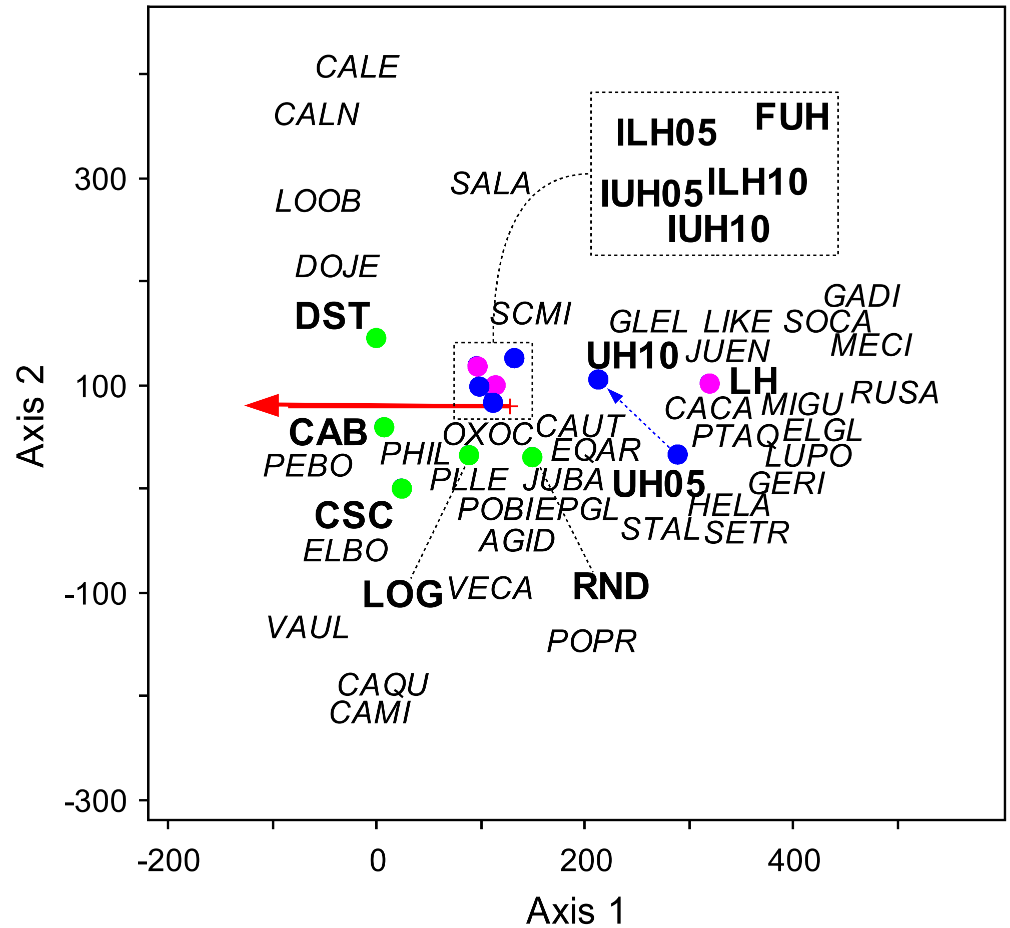

Figure 7. DCA biplot ordination of site vegetation data and species centroids. Green dots are reference sites, blue dots are sites in Upper Halstead Meadow, and purple dots are sites in Lower Halstead Meadow. Four letter italic codes are species centroids. See Appendix 1 for a complete list of species and site codes. The red vectors indicate the direction of increasing average and low water level correlated with the vegetation data. The blue vector shows the vegetation change at the Upper Halstead site from 2005 to 2011.

As a measure of how well the ordination space represents the variation in the original vegetation data, an after-the-fact correlation analysis was done comparing ordination scores with raw vegetation data. The R^2 statistics is the output of this analysis, where 1 is perfect correlation between the ordination and original data, and zero is no correlation. In this DCA, the R^2 value of axis 1, when analyzed for relative Euclidean distance, is 0.663 indicating that 66.3% of the variability in the vegetation composition between sites is explained by their positions along axis 1. Axis 2 represents the second most significant and independent set of vegetation differences between sites. The R^2 value for axis 2 is 0.060, or 6.0% of the variation. Combined, the two axes explain 72.3% of the variation in vegetation composition between sites. Both axes are scaled in units of standard deviations, multiplied by 100. Units of standard deviation are useful in estimating the amount of species turnover that is depicted by the ordination. The original range of site values (not species centroids, which range further) along axis 1 was 3.193 sd units (319.3 on Figure 7 axis 1), and the site range along axis 2 was 1.450 sd (145 on Figure 7 axis 2). An approximate 50% species turnover occurs across a distance of 1 sd, and complete species turnover occurs over a distance of 4 sd. Therefore, the entire spread of sites along axis 1 represents slightly less than one complete species turnover, whereas the spread along axis 2 is somewhat more than a 50% turnover. In addition to sites, individual species centroids are also plotted, as italic codes (see Appendix 1).

The red vectors in Figure 7 represent hydrologic variables overlaid on the ordination. These vectors show how the hydrologic variables are correlated with the vegetation data that structures the axes, spacing of sites, and species centroids. The two red vectors show the average and minimum water levels measured at the sites. The direction of each vector (pointing left) indicates increasing values, with decreasing values in the opposite direction. The vectors are nearly parallel with axis 1, indicating a strong correlation with the primary changes in vegetation that this axis represents. The R^2 values for a Pearson and Kendall Correlation test with the ordination axes are as follows: for axis 1; average water level 0.658, minimum water level 0.611. A third hydrologic variable, the peak water level was not significantly correlated with any axis. No variable tested had an R^2 greater than 0.2 for axis 2. This indicates that slightly more than 60% of the vegetation variation along axis 1 can be explained by either of the two hydrologic variables, average water level or minimum water level, with peak flow having no explanatory power. The remaining ~40% of variation is unexplained by this analysis.

We also analyzed the vegetation and hydrologic data sets using the direct gradient analysis technique canonical correspondence analysis (CCA). CCA constrains the ordination axes to be linear combinations of environmental variables, thus the axes and vectors are the environmental variables to which the vegetation is correlated. Sites were positioned in the ordination space using three hydrologic variables: average water table depth, minimum water table depth (lowest depth water reached), and peak water level. For most sites in the ordination, the hydrologic variables were calculated from the entire water-level dataset for 2005 through 2010. However, for some sites (UH, IUH, and ILH) separate hydrologic variables were calculated for pre- (2005-2007) and post-restoration (2007-2010) in order to assess any changes through time. All study sites and the centroids of plant species are positioned in the ordination space based on their correlation with these three hydrologic variables. In the CCA (Figure 8) axes 1 and 2 are linear combinations of the hydrologic data, and axis 1 is strongly correlated with average water level (R^2 = 0.960) and minimum water level (R^2 = 0.937). Axis 1 has been inverted to match the orientation of the DCA to simplify comparison. Therefore, plots with deep water tables are to the right side of axis 1, with the scale showing percentage of total range. The two red vectors pointing to the left show the direction of increasing values of average and deepest water table depth. Axis 2 is strongly negatively correlated with the peak water level (R^2 = -0.994) with plots having the highest peak water levels at the bottom of the graph. The red vector pointing toward the bottom of the ordination space indicates the direction of increasing peak water level. An after-the-fact correlation test of the final ordination space compared to the original data shows that the ordination, constructed as linear combination of the hydrologic variables, explains 55.9% of the variability in the vegetation data, with all of the explanatory power contained in axis 1. Axis 2, correlated with the peak water level data, did not increase the amount of variability explained. A Monte Carlo test indicated that the correlations detected were statistically significant and not a result of chance (P = 0.01). This is consistent with our DCA analysis in which no direction in the ordination space was significantly correlated with the peak water level data.

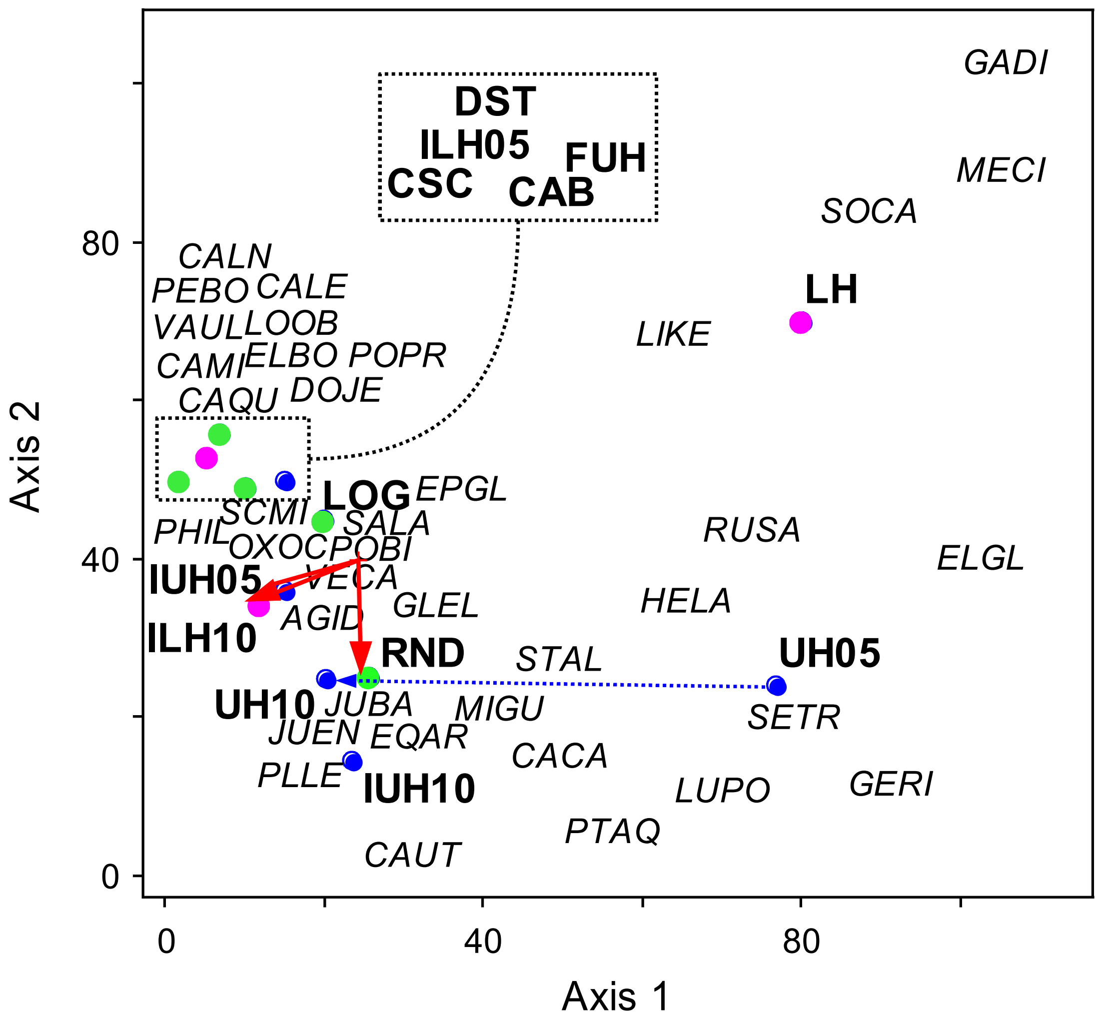

Figure 8. CCA analysis of species and sites based on hydrologic variables. Green dots are reference sites, blue dots are sites in Upper Halstead Meadow, and purple dots are sites in Lower Halstead Meadow. Four letter italic codes are species centroids. See Appendix 1 for a complete list of species and site codes. The red vectors indicate the direction of increasing average, low, and peak water level. The blue vector shows the hydrologic change at the Upper Halstead site from 2005 to 2010.

The dashed blue arrow in Figure 8 shows the hydrologic change in Upper Halstead wells from the pre-restoration period in 2005 (UH05), to the post-restoration period in 2010 (UH10). With respect to position along axis 1, the restored Upper Halstead site (UH10) falls between the 2005 and 2010 Intact Upper Halstead sites (IUH05, IUH10) and is within the range of variation of the reference sites (green dots), such as Round (RND) and Log (LOG) meadows. The restored Upper Halstead (UH10) site experienced higher peak water levels (as indicated by the position along axis 2) than all other sites except Round Meadow (RND) and Intact Upper Halstead in 2010 (IUH10). However, the separation along axis 2 (correlated with peak water level) was found to have no significant affect on vegetation differences. The average and minimum water levels, as indicted by axis 1 position, of Filled Upper Halstead (FUH) are also similar to the reference sites and intact Halstead sites. At FUH, peak flows (axis 2) are among the lowest of all the sites, and this probably reflects efforts made to divert excess water flow off of the largely bare, newly-planted gully fill in order to prevent scouring and erosion. The ordination analysis shows that this managed reduction of peak flows (axis 2) is not likely to have any significant effect on the vegetation composition because the main factors structuring the plant community are average and minimum water levels correlated with axis 1.

Unexpected findings, compaction: The growth of the 2008 *Scirpus microcarpus* plantings over a 14 month period was significantly affected by the level of soil compaction in FUH. A significant linear trend in the data indicates a negative relationship between plant width and soil compaction in the upper 20 cm of soil as described by the equation $y = -0.0128x + 68.136$ ($p < 0.0001$) where y is plant width in cm and x is soil strength in KPa (Figure 9). The correlation coefficient (R^2) for this linear trend is 0.400, indicating that 40% of the variance in plant-width data is explained by changes in surface soil compaction. Other potential effects on plant width include initial size of the transplant, amount of shade, soil and water nutrient levels, and water speed, temperature, and depth. The levels of compaction in the adjacent Intact Upper Halstead site were used as a measure of natural conditions. All compaction measurements in the FUH zone exceeded the natural average compaction (424 KPa) and most readings were higher than the highest natural compaction reading (1429 KPa). The seedlings were planted 45.7 cm (18 inches) apart in June of 2008 and the width and compaction readings were taken in September 2009. Using the above equation, for plants to grow to a width of 45.7 cm and meet their nearest neighbor after 14 months of growth, soil with a compaction of 1750 KPa or less is required. Plants growing in soil with a compaction >1750 KPa are not predicted to grow sufficiently in 14 months to intersect the adjacent planted seedlings. Using data from a companion study not described in this document, the 30% wood chip fill used to repair the 2009 storm damage should result in significantly lower compaction levels than fill with no wood chips (Figure 10). This means that the 2010 transplants growing in the wood chip fill should spread faster than the 2008 plantings.

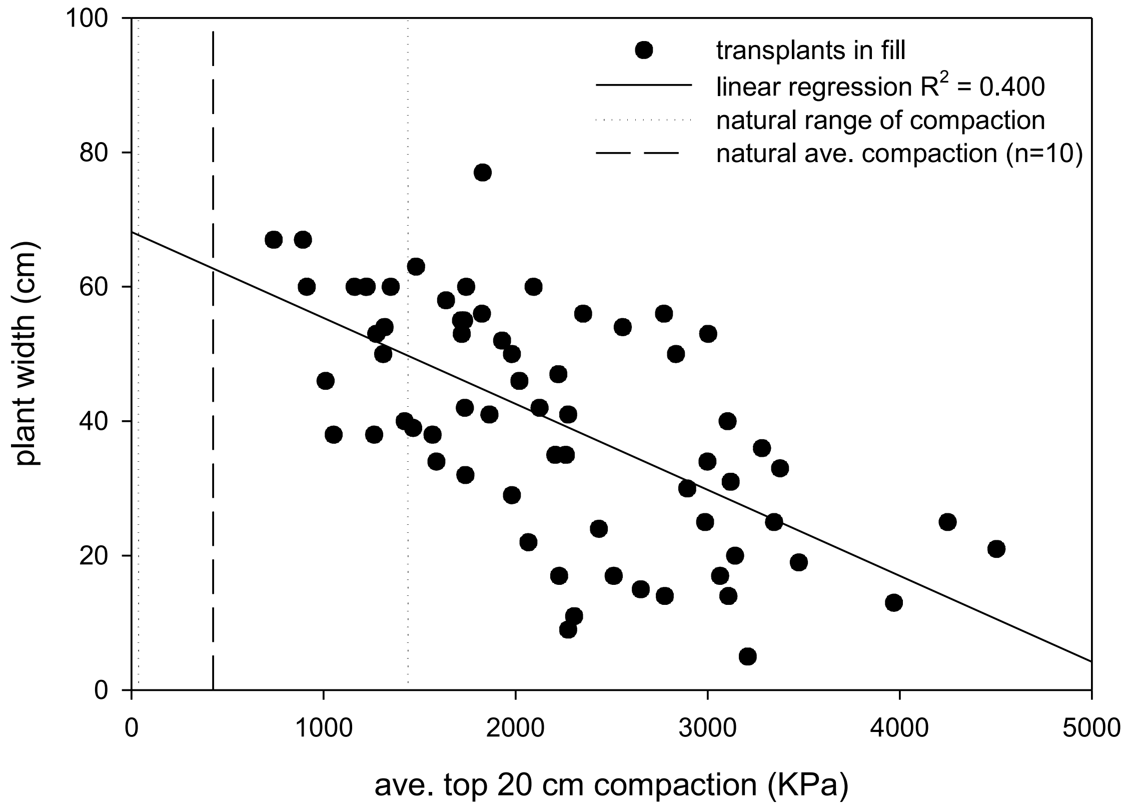

Figure 9. The relationship between the width of Scirpus microcarpus seedlings after 14 months of growth and surface soil compaction. Linear regression is shown as a solid line, see text for equation. All transplants experienced compaction that was higher than the average in reference sites and most were in soil more compact than the most compact natural soils, as indicated by the dashed and dotted lines, respectively.

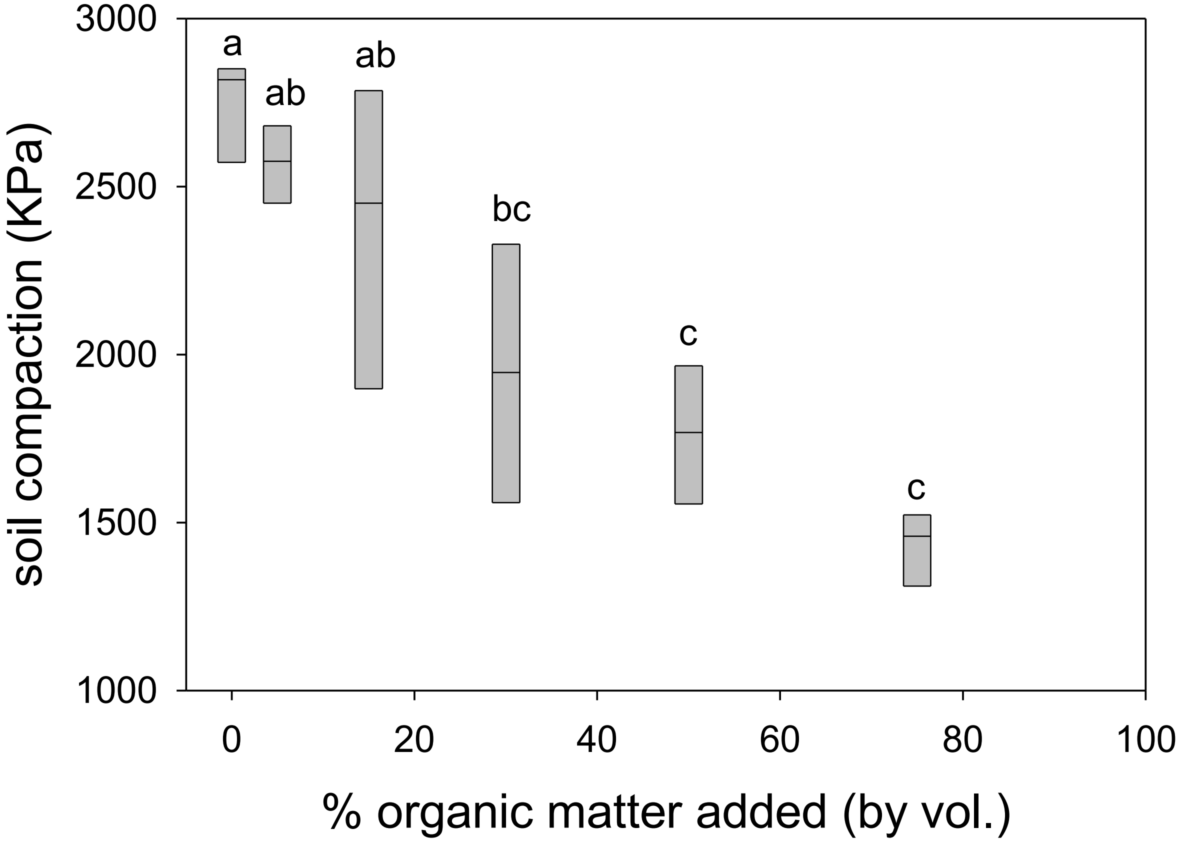

Figure 10. Boxplot showing the different levels of compaction in soils with different proportions of wood chips added. Boxes sharing the same letter are not significantly different from each other, as tested by an ANOVA.

Conclusions

The restoration of Upper Halstead Meadow has achieved its primary goal of establishing a sheet flow hydrologic regime and perennially saturated soils in the area of filled gully as well as the adjacent hydrologically impacted sections of the meadow. The geomorphic goal of creating level topography across the valley width was achieved, and almost immediately upon completion of the gully-fill geomorphic restoration, the water table rose to the surface and sheet flow occurred across the entire Upper Halstead Meadow. However, the storm of Ocotober 14th, 2009 reversed previous success with regard to our geomorphic goal. Significant erosion of placed fill formed a flow channel (Figure 11) that would have continued to widen and deepen without immediate repair. This rain and erosion event provided a critical test, and failure, of two of our design elements: on-contour full-length logs, and the erosion control blanket. During peak flow events of the previous two growing seasons, 2008 and summer 2009, the logs had acted as dams holding back small amounts of water. This ponded water created a head gradient across the log, often resulting in undercutting of the logs and small erosion rills forming. These small erosion events were manageable by hand crews and notches were made in logs (see next to Richard Thiel in Figure 11) to drain ponding where it was observed. However, all of these efforts were tailored to low and moderate flows, and we failed to consider the performance of the logs during high flow events. It is likely that the severe erosion that occurred in October 2009 initiated at a notched or undercut log where a large proportion of all down-valley flow was forced to concentrate by the long log. In retrospect, the smaller erosion events that initiated at logs were harbingers of the larger failure that required heavy equipment to repair. Following the erosion damage, an engineering firm was hired to conduct a risk analysis, and it was determined that not only were the logs likely culprits, but that the shear stress rating of the original erosion blanket was exceeded during the October 2009 storm. As a result of the hydrologic analysis in the risk assessment, design criteria for the Upper Halstead repair and the Lower Halstead project were modified to provide erosion protection against the 10-year flow event occurring before planted vegetation had established a resistant sod, after approximately 5 years. This more stringent erosion protection plan called for heavier erosion blanket, no ponding of water, and more numerous, smaller roughness elements such as coir wattles and shorter log segments, as opposed to relatively few long logs.

Figure 11. Downstream view of the erosion damage caused by the October 14th, 2009 storm. Rich Thiel of the NPS stands at a long, on-contour log with a notch cut out directly over the eroded gully. Note the long roots and rhizomes dangling from planted Scirpus on the left bank, in the foreground.

The project goals for the hydrologic regime have been met: well readings in restored Upper Halstead are within 1 standard deviation of the intact portions of Upper and Lower Halstead Meadow as well as the 5 reference meadows. The un-restored Lower Halstead meadow still has distinctly different water levels, but the success of the Upper Halstead pilot project demonstrated that geomorphic restoration by gully-filling to the existing meadow grade can restore sheet flow hydrology.

The project goal of seedling survival greater than 75% was met during the first growing season, 2008. No assessment of survival was made during 2009 prior to the October storm, where up to a third of the plantings may have been washed out, buried under redeposited sediment, or killed during the repair earthwork. The areas where plants were lost in the 2009 storm were replanted in the summer of 2010, and seedling survival will be assessed in the summer of 2011. Plant width was assessed in

September 2009 and shows that 28 out of 110 plants measured had spread to a width of 51cm (20 inches) or greater. Therefore, after 2 growing seasons, 25% of the plants had spread far enough to be in direct contact with plants in adjacent rows. By the summer of 2010, many of the 2008 plants were intergrown to the point where it was impractical to determine the widths of individual plants. This indicates that our second vegetation goal of increasing cover was met.

Initial 2008 planting density and planting ratio deviated slightly from the specified values, but no specific targets for these metrics were set, and the deviations do not appear significant. As expected, the vegetation goals of achieving a plant community in Upper Halstead similar to those in the intact Halstead and reference sites, has taken longer to achieve than the hydrologic goals. Several to many years are required for transplants to spread and form a dense sod and for the pre-existing upland plant community to be out-competed and replaced by a wetland plant community. However, it is clear that this transition is occurring, and the Upper Halstead site is now more similar to the intact and reference sites than to its previous vegetation composition or that of the unrestored Lower Halstead. The planted community in the Filled Upper Halstead site is maintaining its similarity to reference sites and not transitioning to a different and undesired state.

Plants are a critical component to meadow stability. Large runoff events from spring snow melt and rainstorms easily erode bare, exposed soil, and initiate gully formation. Once a gully forms it concentrates water flow and exacerbates erosion, eliminating the sheet flow hydrologic regime, lowering the water table, and altering the plant community. In a dense community of wetland plants stems, leaves and litter slow the flow of water and limit its erosive potential. Most importantly, the tightly woven network of roots and rhizomes bind the soil together and are extremely resistant to erosion. Establishing a complete cover of densely-rhizomatous plants (*Scirpus microcarpus* and *Glyceria elata* are two such species) is the primary vegetation goal. Without these plants the soil can erode during large flows. The 2008 plantings are spreading rhizomatously and by summer of 2010 achieved between 19% and 47% cover at the two plots that survived the 2009 flood: wells 96 and 87. In addition, the plant width data from 2009 show that plants throughout the fill zone are expanding below ground and sending up new shoots, increasing above ground cover. The plantings in the storm repair fill area have not yet had a full growing season, so their success is difficult to evaluate. However, because the storm fill contains 30% wood chips that can significantly reduce soil compaction, it is hoped that these plants will spread well and develop suitable root and shoot density to bind the soil and stabilize the meadow. Below ground plant production will cause an increase in soil organic matter that will be detectable over longer time frames than this study, perhaps in 5 to 10 years.

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Appendix 1. Species and site codes used in ordination plots.

Species	Species code	Site	Site code
Achnatherum occidentale	*ACOC*	Cabin	**CAB**
Agrostis idahoensis	*AGID*	Crescent	**CSC**
Agastache urticifolia	*AGUT*	Dorst	**DST**
Artemisia douglasiana	*ARDO*	Filled Upper Halstead	**FUH**
Bare ground	*BARE*	Intact Lower Halsted 2005	**ILH05**
Calamagrostis canadensis	*CACA*	Intact Lower Halsted 2010	**ILH10**
Carex lemmonii	*CALE*	Intact Upper Halsted 2005	**IUH05**
Carex lenticularis	*CALN*	Intact Upper Halsted 2010	**IUH10**
Castilleja miniata	*CAMI*	Lower Halstead	**LH**
Calyptridium monospermum	*CAMO*	Log	**LOG**
Carex nebrascensis	*CANE*	Round	**RND**
Camassia quamash	*CAQU*	Upper Halstead 2005	**UH05**
Carex utriculata	*CAUT*	Upper Halstead 2010	**UH10**
Carex vesicaria	*CAVE*		
Deschampsia caespitosa	*DECA*		
Dodecatheon jeffreyi	*DOJE*		
Eleocharis bolanderi	*ELBO*		
Elymus glaucus	*ELGL*		
Epilobium glaberrimum	*EPGL*		
Equisetum arvense	*EQAR*		
Gayophytum diffusum	*GADI*		
Geranium richardsonii	*GERI*		
Glyceria elata	*GLEL*		
Helenium bigelovii	*HEBI*		
Heracleum lanatum	*HELA*		
Hypericum anagalloides	*HYAN*		
Juncus balticus	*JUBA*		
Juncus ensifolius	*JUEN*		
Lilium kelleyanum	*LIKE*		
Lotus oblongifolius	*LOOB*		
Lupinus polyphyllus	*LUPO*		
Mertensia ciliata	*MECI*		
Mimulus guttatus	*MIGU*		
Mimulus laciniatus	*MILA*		
Oxypolis occidentalis	*OXOC*		
Pedicularis attollens	*PEAT*		
Perideridia bolanderi	*PEBO*		
Philonotis	*PHIL*		
Phacelia mutabilis	*PHMU*		
Platanthera leucostachys	*PLLE*		
Polygonum bistortoides	*POBI*		
Poa pratensis	*POPR*		
Pteridium aquilinum	*PTAQ*		
Rumex salicifolius var. denticulatus	*RUSA*		
Salix lasiandra	*SALA*		
Saxifraga oregana	*SAOR*		
Scirpus microcarpus	*SCMI*		
Senecio triangularis	*SETR*		
Solidago canadensis	*SOCA*		
Spiranthes porrifolius	*SPPO*		
Stachys albens	*STAL*		
Torreyochloa pallida	*TOPA*		
Vaccinium uliginosum	*VAUL*		
Veratrum californicum	*VECA*		