# Lessons from the Upper Halstead Meadow pilot restoration: soil compaction, seeding, and hydrology

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## INTRODUCTION

In September 2007 a large erosion gully in Upper Halstead Meadow was filled with 7,200 cubic yards of soil. In the spring of 2008 more than 40,000 seedlings of three native wetland plant species were planted in the filled meadow. The goals of this restoration program are to rebuild the natural topography and landforms of Upper Halstead Meadow, reestablish a sheetflow hydrologic regime, restore a native wetland plant community, and restart the critical wetland ecosystem functions sedimentation and soil carbon storage. Post-restoration site monitoring revealed that some design elements resulted in unforeseen consequences and unmet project goals. Plant growth was uneven across the site and fill placed into the former gully may have been over-compacted, contributing to the patchy growth. Logs that had been placed on-contour ponded water, which triggered undercutting of the logs, flow concentration, and erosion. On October 13th 2009 ~20 cm of rain that fell in 24 hours washed out a gully in the recently placed fill. Several studies were implemented to investigate apparent soil over-compaction, slow plant growth, and undesirable hydrologic flow patterns at high discharge. We present here the results of those experiments and how those results have been used to improve the design of the larger Lower Halstead Meadow restoration.

A small experimental wetland was constructed to determine the compactability of soil with different levels of wood-based organic matter (OM) amendments. In addition we determined whether wood-based amendments caused changes in soil stability, hydraulic conductivity or shrink and swell properties. The experiment was inadvertently destroyed before the hydraulic and shink/swell measurements could be made, but the other results are presented. These results were used to develop specifications for soil amendment and fill compaction used to repair the Oct 2009 storm damage in Upper Halstead, and fill to be placed in Lower Halstead Meadow in 2012.

A randomized field sampling of fill compaction and seedling growth in the Upper Halstead pilot project area was used to determine whether compaction and plant growth were correlated. These data were used in making decisions on the design of the Lower Halstead restoration. Establishment of a dense plant community of self-sustaining native sod-forming plants that resist erosion and maintain a sheetflow hydrologic regime is critical to the long-term stability of Sierra Nevada wet meadows. Factors that slow plant establishment lengthens the time that bare sediment in a newly restored wetland is vulnerable to erosion.

Direct seeding below erosion control blanket was tested as a method of establishing desirable plants on bare mineral sediment. Collecting and sowing native plant seed is an inexpensive method of establishing plants to a restored site compared with growing seedlings in a nursery. All three of the species raised in the greenhouse, *Scirpus microcarpus*, *Glyceria elata,* and *Oxypolis occidentalis,* produce viable seed, but it was unknown whether these seeds could be directly sown to produce seedlings in a field restoration setting. Direct seeding is a potential method for establishing a plant sod in a cost-effective manner. A field experiment using the three target species was conducted to determine emergence rates in different flow conditions.

Finally, to quantify the hydrologic regime of Halstead Meadow, a series of water level loggers were installed in key locations. Ground and surface water levels were measured every 20 minutes allowing a more accurate calculation of flow through the meadow. These data were critical for determining the erosive potential and level of erosion control required at the site. In addition, the logger data allowed for the calculation of peak flow, base flow, and estimates of evapo-transpiration and groundwater flow.

The results and conclusions of these projects are presented here in quantitative summary form, and we outline key lessons learned during the Upper Halstead pilot wetland restoration program. This information is critical for the design and upcoming implementation of the Lower Halstead restoration, and also provides insight into the processes that maintain naturally functioning mountain wetlands.

## METHODS

### SOIL AMENDMENT EXPERIMENT

The influence of % wood chip volume on soil compaction was tested using a factorial experiment implemented in a 3 foot deep, 12 foot wide, 70 foot long trench. The trench was constructed at the Wolverton staging area, the unused staging area near the Sherman Tree parking. Five levels of wood chips by volume mixed with sub-soil fill dirt were tested: 0%, 5%, 15%, 30%, 50% and 75%. Treatment and control (0%) plots were individual cells 4 foot by 4 foot by 3 foot deep (48 $ft^3$ in volume). Water-proof pond liner was placed on the trench bottom to maintain saturated conditions within the trench. Two 500-gallon water tanks were used to water the trench and maintain soil saturation.

A bark humus topsoil amendment experiment was also performed within the same trench. The cells were constructed as described above, except that each cell was 1 foot deep. The 5 treatment levels and control were identical to the wood chip treatments, except that instead of wood chips bark humus was tested. We used 4 replicates of each treatment level (2 with wood chips, 2 with bark humus) and control, all of which were evenly interspersed throughout the trench to avoid potential spatial bias (see Figure 1).

Wood chips and bark humus were obtained from stockpiles in Sequoia National Park. The volume of wood added to each treatment was measured using graduated buckets. Cells were filled in one-foot lifts using 4ft x 4ft x 1ft plywood forms with dirt placed in them by a backhoe and the amendment added and mixed by hand. A 1-foot wide buffer of pure fill dirt (0% amendments) was placed completely around and between each cell. The buffer provided walking space to move between cells without disturbing the test soil and prevented direct hydrologic and compression interaction between treatments. Once the test cells and buffer were filled to 1 foot depth, the forms were lifted and moved along the trench until all test cells and buffers were filled. After all cells and buffers within a lift were filled, the entire one-foot thickness of soil was wetted and compacted evenly using a Wacker brand jumping jack plate-tamper. The boundaries between buffer and test cells were marked with flags and spray paint during each lift and marked with rebar and rope after final compaction to ensure accurate re-location of the cells.

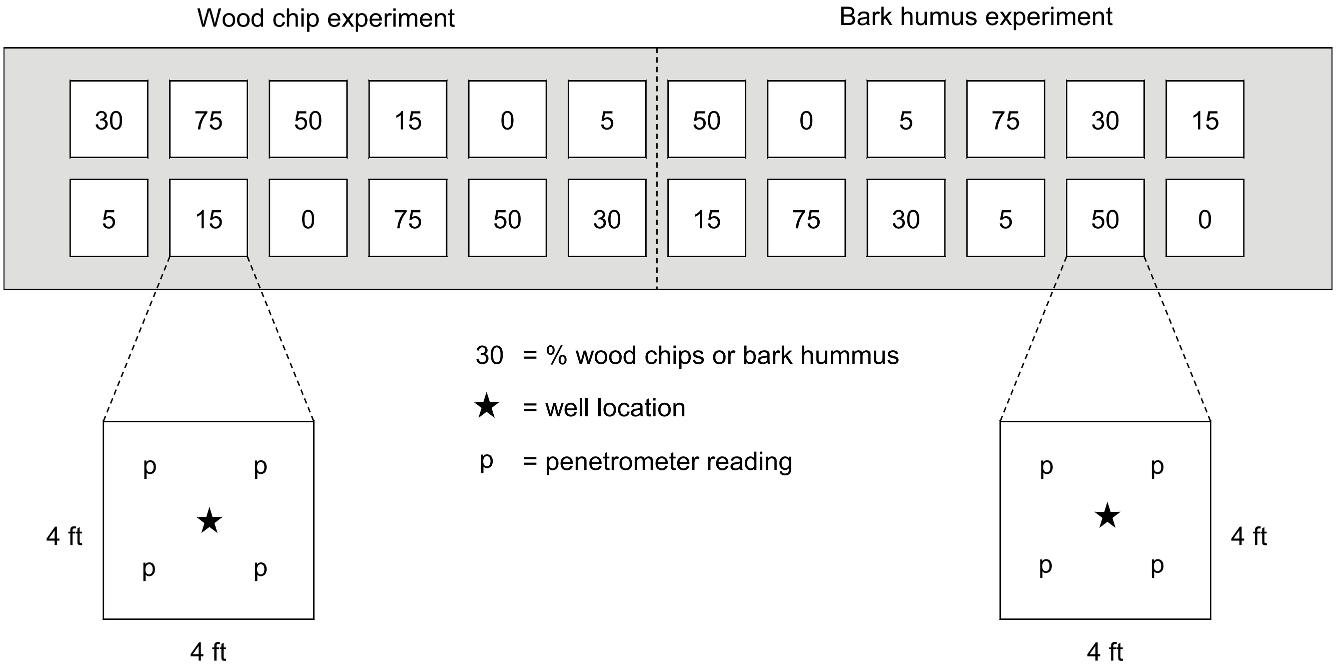

*Figure 1. Study design for the test plots (numbered white squares) within the 3 foot deep lined trench filled with subsoil equivalent to the 0% treatments (grey).*

A soil penetrometer (Spectrum Technologies SC 900) was used to determine the force in KPa required to push a probe 20 cm vertically down into the soil. After six weeks of continuous water saturation following the initial installation, four penetrometer measurements were made in each cell each 1 foot corners (Figure 1). Readings were automatically logged in 2.5 cm depth. The 8 readings within the top 20 cm were averaged to produce a single point reading, and the 4 point readings within each cell were averaged to yield a compaction data point for the treatment replicate.

The surface of the saturated treatments was surveyed to determine whether soil settling or swelling occurred. An initial survey was made immediately after soil saturation. Unfortunately, the surface of the test trench was accidentally disturbed by heavy construction equipment before a second round of survey points could be taken. Therefore quantitative measures of settling or swelling were not made. However, qualitative observation suggested no mounds or depressions had formed due to swelling, settling, or shrinking of the treatments within their cells. We had also intended to conduct hydraulic conductivity experiments using a pump test, but these were similarly prevented by the destruction of the test site.

To test the stability of the subsoil treatments, a 4” (10 cm) diameter vertical hole was augured in the wood chip treatments to a depth of 2.5 feet (75 cm) in the bark humus treatments. The hole was left open (but covered with a sheet of plywood to prevent sediment transport into the hole from the surface) to allow sediment to collapse off the hole walls. After 1 year depth to hole bottom were remeasured and a depth of collapsed material calculated.

Linear regression and analysis of variance (ANOVA) were used to determine whether there were significant organic matter addition treatment effects on soil compaction and soil collapse.

## UPPER HALSTEAD COMPACTION AND PLANT GROWTH

Field measurements of compaction and seedling growth were made in the filled and planted area of Upper Halstead Meadow on September 16th 2009 14.5 months after the plants were installed (~5 months of growing season). To ensure a representative sampling from the entire area while also maintaining independence and lack of bias, the 1000 foot length was stratified into 14 sections, delineated by felled trees, and a point was randomly selected within each section for study.

At each sample point the nearest five planted individuals of *Scirpus microcarpus* were selected as study plants. The other 2 planted species, *Oxypolis occidentalis*, and *Glyceria elata*, were not analyzed because they were planted in lower densities, the condition of seedlings delivered from the nursery was highly variable, and neither species produces tillers from rhizomes like *S. microcarpus*. Therefore, making measurements of lateral spread was not possible. Several portions of the study site were planted with larger *S. microcarpus* plants, and one site planted in the fall of 2007 received a higher density of individuals. Points that fell within these areas were relocated.

At each selected plant the maximum between the two furthest shoots and the maximum leaf height was measured. Soil compaction in the top 20 cm (the rooting zone) was measured with a soil penetrometer 40 cm north of the plant center.

In addition, several haphazardly located penetrometer readings were taken within the intact natural wetland in Upper Halstead, in the formerly dry part of Upper Halstead Meadow that was rewetted by restoration, in sandy storm deposits left by the October 2009 flood event, in the 30% wood-chip gully fill from the Oct 2009 repair, in the 2008-planted zone after 2 years, and in areas planted in 2010.

Linear regression and analysis of variance (ANOVA) were used to determine whether there were significant soil compaction effects on plant width and height. Haphazardly measured data were not included in any statistical analyses.

## UPPER HALSTEAD SEEDING EXPERIMENT

To determine the field seedling emergence rates of three target species, we seeded plots in Upper Halstead Meadow with *Scirpus microcarpus, Glyceria elata,* and *Oxypolis occidentalis.* Seed was collected on site in October 2009 and cold-wet stratified over the winter. Seeds were planted in June 2010. Six sites were selected within the filled gully area of Upper Halstead. Three in saturated but low flow areas, and three in actively and constantly flowing areas. Within each of the two flow scenarios, three sites were chosen to be as similar as possible and high and low flow sites differed only in the water discharging across them. A single site consisted of a 60 cm by 240 cm rectangle, oriented perpendicular to flow, divided into four adjacent 60 cm square plots. Each plot was randomly assigned a treatment of seeds of one of the three species, or a control with no added seeds. An undisturbed buffer 5 cm wide was designated along the edge of each plot, reducing the actual treatment plots to 50 $cm^2$ with a 5 cm buffer to the surrounding meadow and a 10 cm buffer between treatments (resulting from two abutting 5 cm buffers).

One hundred well-developed seeds were counted using a dissecting microscope for placement in each treatment plot. The sites were planted on July 15th 2010. Sand bags were placed upstream of each study site to dewater the area while installing the experiment to prevent seeds from washing downstream before the erosion blanket could be replaced. Existing erosion blanket at the study sites was cut out and removed. The top 2 mm of soil at each study site was scraped off and removed. 500 $cm^3$ of imported upland fill dirt (left over from the Oct 2009 gully repair) was well mixed with the 100 treatment seeds and spread evenly over the 2500 $cm^2$ study plot to a depth of 2 mm and tamped flat. The control was treated similarly, but without mixing seeds into the soil. New erosion blanket was placed over the site once all plots were treated. The number and species of seedlings that emerged in each plot were counted on September 21st 2010. A total of 3 within-treatment counts (e.g. *Scirpus* seedlings that emerged in the *Scirpus* treatment plot) for each the low and high flow sites. Seedling emergence in control plots were also counted in the 3 non-treatment plots per site (e.g. the total number of *Scirpus* that emerged in the control, *Oxypolis*, and *Glyceria* treatments). This resulted in 9 total plots from which the control averages are derived, three plots per site and three sites per low or high flow set. The control count represented the background seedling emergence rate from seeds that either washed into the plots or were left after the intial earthwork.

The seeding experiment generated count data with a large number of zero's and low value counts, we did not assume that the data were normally distributed. A Poisson distribution was used to approximate the low-frequency count data. A c-test was used to compare mean counts for all treatment pairs with a significance level of alpha = 0.05.

## HYDROLOGY

To calculate the Upper and Lower Halstead Meadow water budget all surface water inputs and outputs were measured, as were groundwater levels within each meadow. Pressure transducers (Hobo U-20, Onset Computer Corp.) were installed to record water level every 20 min at fixed locations in Upper Halstead Creek where it enters Upper Halstead Meadow, at the double culverts outletting Upper Halstead to Lower Halstead, at the check dam outletting Lower Halstead, at the culverts under the highway where an East and West unnamed tributary enter Lower Halstead meadow, and at well 13 in Upper Halstead and well 73 in Lower Halstead. A barometric logger was placed above ground on the margin of Upper Halstead Meadow to record atmospheric pressure and air temperature. Atmospheric pressure readings were subtracted from well logger readings to obtain water-pressure-only values that were converted into water column heights. At the three culvert locations water height was converted into discharge using the equation for flow through a circular weir (Addison 1941). Because these culverts are inlet-controlled the circular weir equation is appropriate. Low-flow discharge values were independently measured at the double culverts outlets using a Baski flume, and these readings corresponded very well to the calculations based on inlet water level using the circular weir formula.

At the two surface flow sites without culverts – Upper Halstead Creek as it enters the meadow and at the check dam below the meadow – notched rectangular weirs were installed to measure water-level to discharge relationship. For these sites the Kindsvater-Carter equation was used to convert water level to discharge. At the two well sites, the change in water storage for the Upper and Lower Halstead Meadows was calculated based on the rise and fall of the water table. A discharge or storage rate was calculated as the drop or rise in the water table. The readily available specific yield of the soil was estimated to be 0.26, an average value for loamy sand textured soil (Loheide 2005). Each well was also assumed to represent the entire water table surface level within their respective meadow halves, thus providing the necessary length and width dimensions to multiply the water depth by to calculate a volumetric discharge.

The basic water budget equation (Inputs = Outputs + Change in storage) was balanced for each meadow half. Only a late-summer, low-flow, precipitation-free period was considered for calculation of water balance because no on-site precipitation data were taken, and spring snowmelt produces significant non-point-source surface inflow to the meadow. Daily precipitation data shown in the results were averaged between the two closest automated sites, Wolverton and Giant Forest. They are used only to illustrate the timing and relative magnitude of precipitation events but not used as an absolute measure of on-site precipitation or for water balance calculations. It should be noted that rain events in this mountainous region can be very patchy: the large rain event shown for mid-October 2009 as ~ 80 mm was hand measured at a location nearer to Halstead Meadow as ~200 mm.

Two critical water fluxes were not directly measured and are estimated by analyzing the surface flow and water level data: evapotranspiration (ET) and groundwater flow. Diurnal fluctuations in the water balance (once inputs, outputs, and change in storage have been accounted for) synchronous with fluctuations in daily temperature were interpreted as the signal of ET. A simple model based on daylight hours and on-site air temperature was built to estimate ET and account for the diurnal residuals in the water balance. The remaining systematic residuals (a balance above or below zero) were assumed to be groundwater flows, with random oscillations attributed to measurement error.

A second independent method of estimating ET was used to verify the water balance. This method requires only well water level data (Loheide 2005, 2008) and air temperature data, so we were able to use several different time periods and compare results. First, multi-day trends in the selected time periods of interest are calculated for the groundwater level. The data are then detrended using the calculated linear regression equation. The residuals then represent the daily drowdown due to ET and the nightly recovery due to groundwater flow to recharge the depleted soil. Groundwater flow is constantly occurring, during day and night, while the only significant ET is assumed to occur during daylight hours. The groundwater recharge rate is calculated as the slope of water table rise after ET shuts down for the day. The ET rate is slope of the water table drop during the sunny part of the day, plus the groundwater recharge rate because to affect a drop in the water level, ET must outpace groundwater recharge. As with the water balance method, this water table decline method is sensitive to values of readily available specific yield (Sy). This is a difficult value to directly measure and we have estimated a value of 0.26 based on an observed soil texture of loamy sand at well 13 where water level data were taken. However, parts of Upper Halstead Meadow have finer textured soils, so it should be noted that in the methods we use Sy and ET are directly related, so that a halving of Sy will result in a halving of the calculated ET.

## RESULTS AND DISCUSSION

### SOIL AMENDMENT EXPERIMENT

Neither soil compaction for the top 20 cm nor the soil collapsing into a vertical hole at each treatment level (% organic matter added, by volume) were significantly different between the wood chip vs. the bark humus experiment. Therefore, these data were lumped to provide four replicates for each treatment level, increasing statistical power. In figures 2 and 3 stacked bars are displayed to show the overlap in results from the two amendment types.

The addition of organic matter reduced the compaction of saturated soil. Linear regression analysis indicated a statistically significant ($p<<0.001$) negative correlation between the percentage of organic matter added, by volume, and soil compaction. This linear model explained 73.6% of the variability in the compaction data and estimated a decrease in soil compaction of 17.5 KPa for every 1% of organic matter added by volume, with an estimated y-intercept (0% organic matter) of 2632 KPa. The discreet treatment levels were also analyzed using ANOVA to determine which treatments differed significantly. The 0%, 5%, and 15% treatments were not significantly different from each other. In addition, the 30%, 50%, and 75% treatments were not differ significantly from each other. However, all treatments of 30% or greater have significantly less compaction than the 0% treatment. All pairwise comparisons are illustrated in Figure 2. The treatment with the lowest amount of organic matter addition that produced a statistically significant difference 0% OM, was 30%.

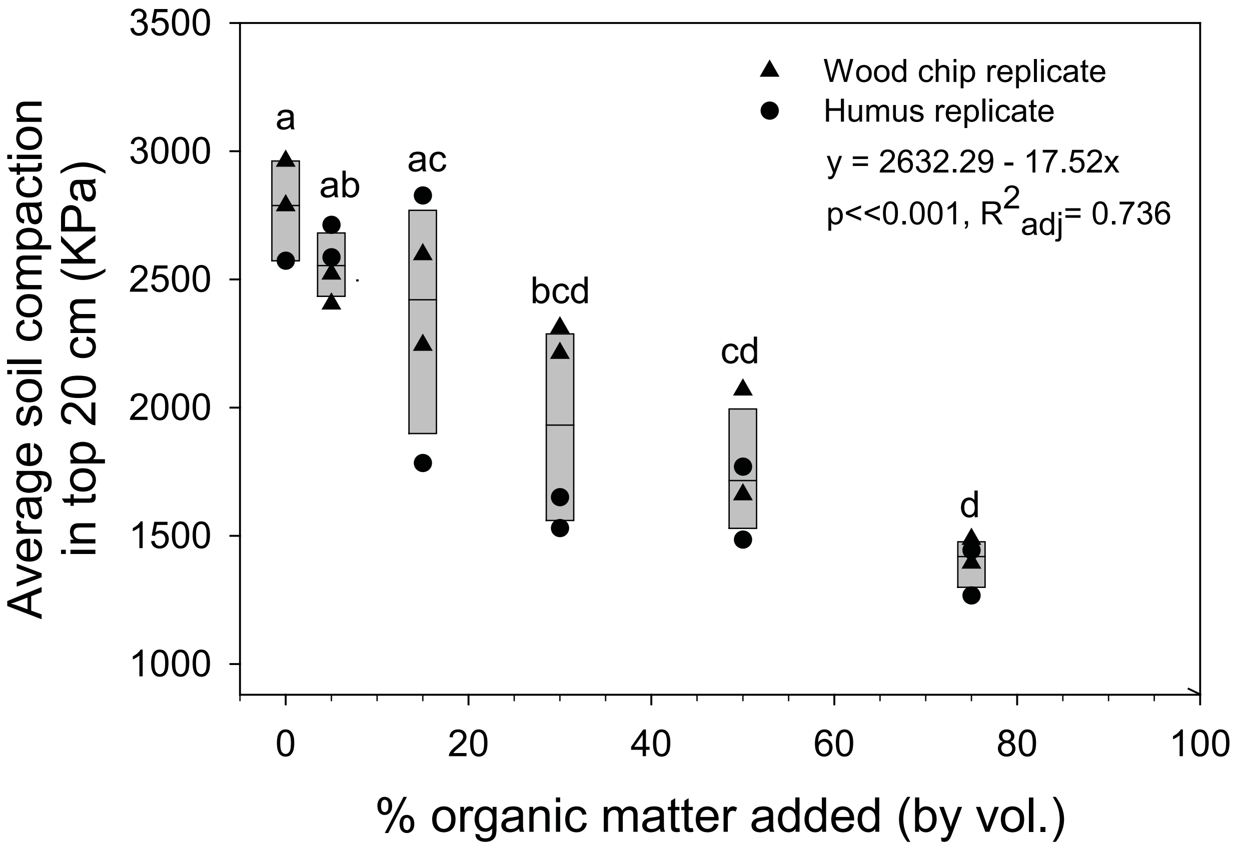

*Figure 2. Average soil compaction (KPa) for 6 levels of organic matter addition, n=2 wood chip and n = 2 humus shown as black triangles and dots (respectively). Box-plots show 25-75 quartile range and median (horizontal line). Treatments with identical letters are not significantly different. Linear regression (dashed line) is shown.*

There was no statistically significant difference in the depth of soil that collapsed into vertical holes for any treatment (Figure 3). Linear regression analysis showed no trend significantly different from a zero slope line, and ANOVA indicated no differences between treatments. This indicates that addition of OM did not significantly affect the stability of a vertical soil face.

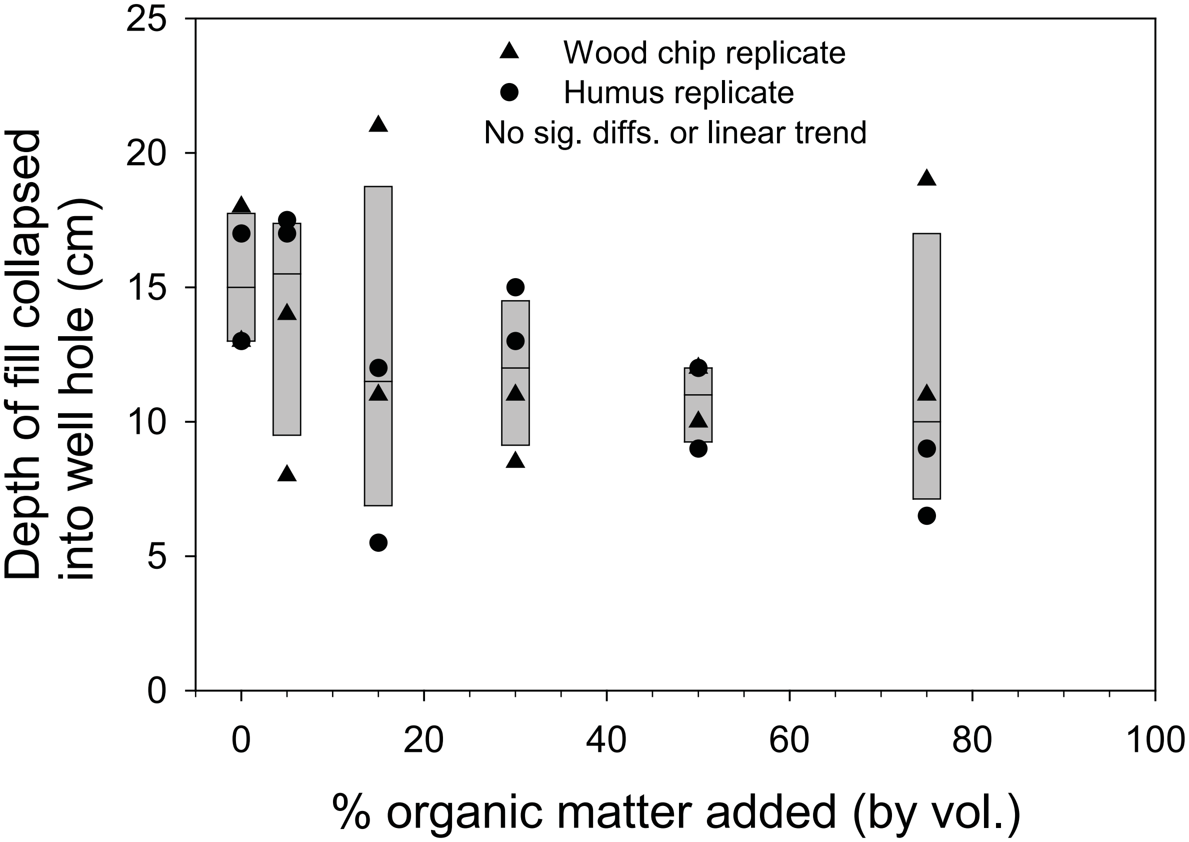

*Figure 3. The amount of added organic matter did not significantly affect the amount of soil collapsed into a vertical hole. The data from the 6 treatment levels of organic matter addition with four replicates (2 each of wood chips and humus) are shown as black triangles and dots (respectively). Grey box-plots show the 25-75 quartile range and median (horizontal line). No regression line or ANOVA results are shown because neither analysis produced statistically significant results.*

## UPPER HALSTEAD COMPACTION AND PLANT GROWTH

Plant height and diameter were significantly negatively correlated with soil compaction (Figure 4). A significant linear regression trend ($p<<0.001$) explained 42.6% of the variation in plant height with an estimated y-intercept (compaction = 0 KPa) of 69.3 cm and height decreasing an estimated 0.012cm per 1 KPa. Plant diameter was described by a significant linear trend ($p<<0.001$) that accounted for 38.6% of variability in the data and estimated a y-intercept of 68.1 cm with a decrease of 0.013 cm of plant width per 1 KPa. All field measurements of fill compaction exceeded the maximum measured value within the natural wetland (589 KPa). A significant portion (~40%) of the patchy slow plant growth that we noted in the field is related to compaction in the top 20 cm of fill.

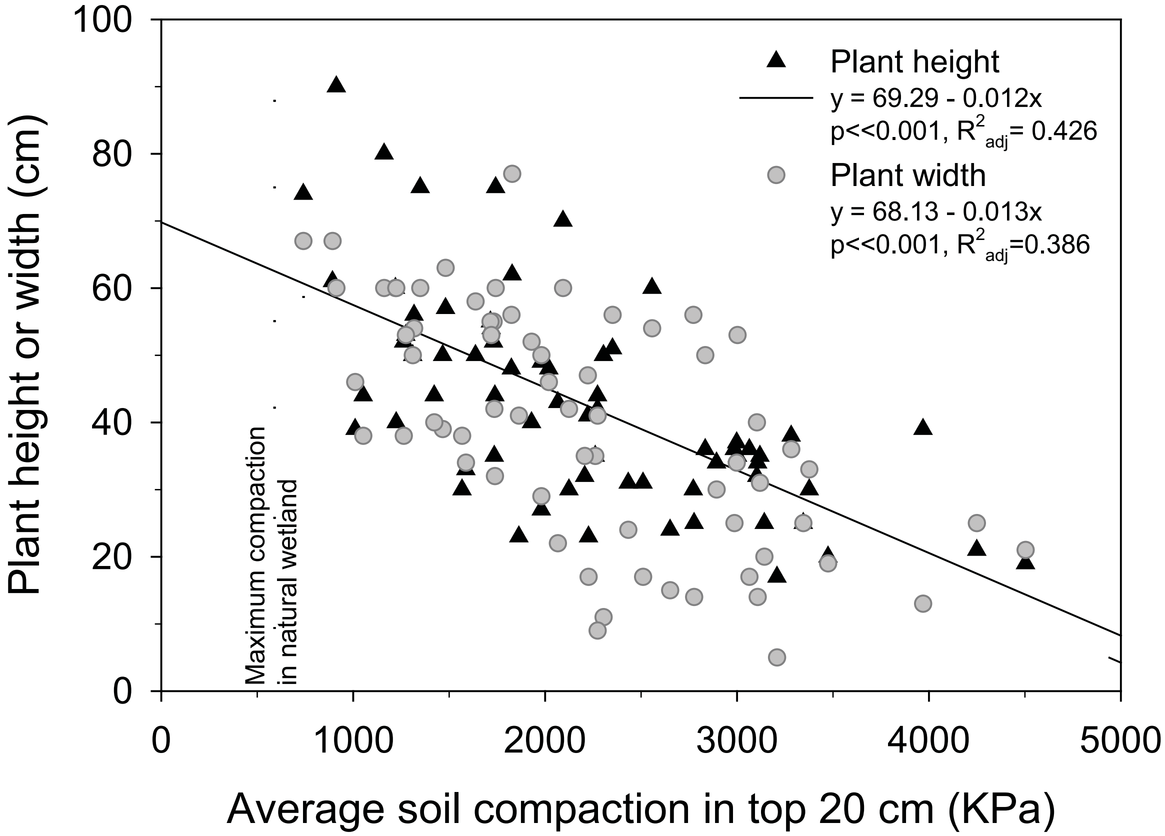

*Figure 4. Both plant height and width decreased significantly with increasing soil compaction. Individual plant height points are shown as black triangles, plant width as gray circles. The linear regression lines for height and width are solid and dashed. The maximum measured value (589 KPa) of natural wetland compaction is shown as a dotted vertical line.*

Figure 5 compares compaction in the measured areas of Upper Halstead Meadow. Planted areas showed a wide range of compactions and higher median compaction values than natural wetland or formerly dry meadow areas. The 30% by volume wood chip mix that was used to fill the gully from the Oct 2009 storm shows values intermediate between undisturbed ground and planted fill. These values for a 30% wood chip mix are reasonably close to those obtained in the experimental trench wetland (see Figure 2).

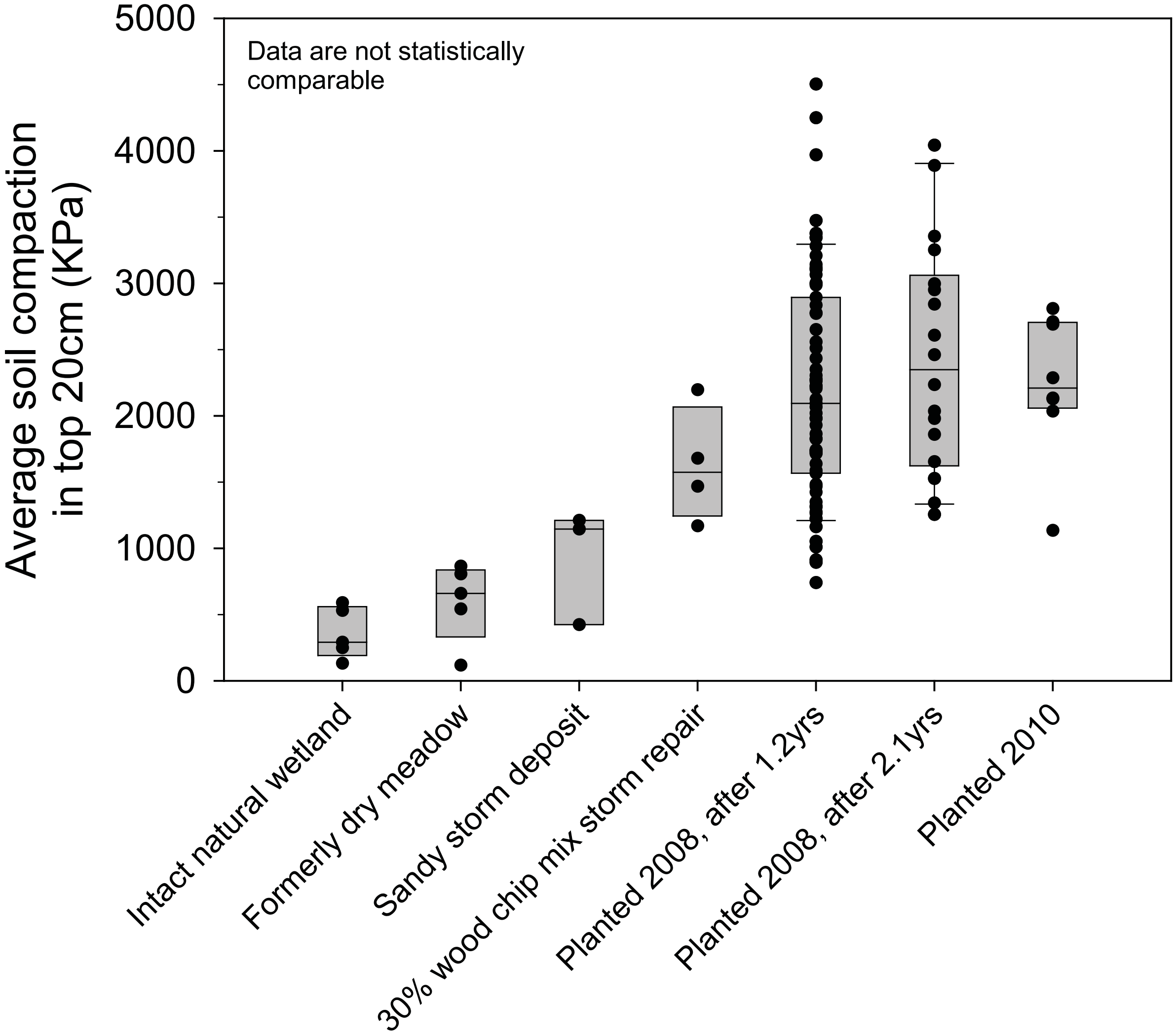

*Figure 5. Qualitative comparison of soil compaction in Upper Halstead Meadow. Some of these data were not collected as part of a randomized sample design, and are thus not statistically comparable.*

UPPER HALSTEAD SEEDING EXPERIMENT

In the low flow treatment *Glyceria elata* had the highest average emergence rate (42.3 seedlings per plot), followed by *Scirpus microcarpus* (12.3 seedlings per plot), and *Oxypolis occidentalis* (2.7 seedlings per plot) (Figure 6). All low flow treatments were significantly higher than their respective control plots that had average seedling counts of less than 1 plant. The high flow treatments of *Glyceria* (5.0 seedlings per plot) and *Scirpus* (0.3 seedlings per plot) were both significantly lower than their respective low flow treatments while the high flow *Oxypolis* treatment (4.3 seedlings per plot) was not significantly different from its low flow treatment. The only high flow treatment to significantly differ from its respective high flow control was *Oxypolis*.

The high flow treatment significantly reduced emergence of the two small-seeded species *Glyceria* and *Scirpus*, but had no effect on the larger-seeded *Oxypolis*. Smaller seeds may be more easily washed downstream by flowing water whereas larger and heavier seeds might require higher flows to move, and may stay trapped under the erosion blanket. However, the background (control) emergence rate does not follow this seed-size pattern. The only control seedling counts that were significantly greater than zero were the low- and high-flow controls for *Glyceria*; both *Scirpus* and *Oxypolis* had zero, or statistically-indistinguishable-from-zero emergence. This pattern may reflect the relative intensity of seed rain from different species onto the site, with *Glyceria* dispersing sufficient seed to produce seedling emergence at both the low- and high-flow treatments. Significantly more *Glyceria* emerged in the high-flow treatments, possibly indicating that flow facilitates transport of seeds that are then entrapped and begin growing on-site.

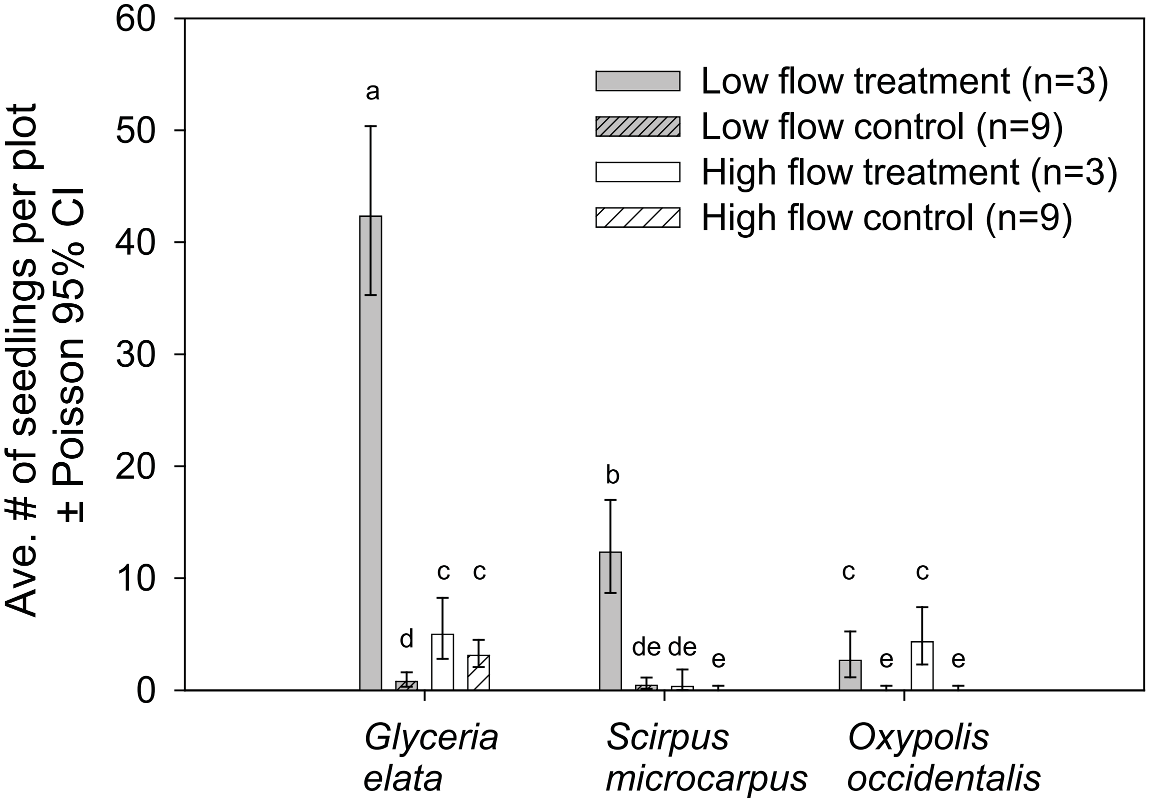

*Figure 6. Seedling emergence for three species at control and treatment (100 seeds added) plots in low and high flow sites. Confidence intervals and pairwise comparisons of seedling counts were calculated with Poisson c-tests. Plots that share a letter are not significantly different (α = 0.05) from each other. See Table 1 for complete pairwise p-values.*

*Table 1. The p-values resulting from pairwise Poisson c-tests of the seedling counts at each plot. Statistically significant differences in counts are indicated with asterisks at the following levels of p:* $0.05 > p^{*} \geq 0.01 > p^{**} \geq 0.005 > p^{***}$.

| Pairwise p-values | GLEL Low Trt. | GLEL Low Ctl. | GLEL High Trt. | GLEL High Ctl. | SCMI Low Trt. | SCMI Low Ctl. | SCMI High Trt. | SCMI High Ctl. | OXOC Low Trt. | OXOC Low Ctl. | OXOC High Trt. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| GLEL Low Treatment | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| GLEL Low Control | <<0.0001*** | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| GLEL High Treatment | <<0.0001*** | <<0.0001*** | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| GLEL High Control | <<0.0001*** | 0.0005*** | 0.0962 | -- | -- | -- | -- | -- | -- | -- | -- |
| SCMI Low Treatment | <<0.0001*** | <<0.0001*** | 0.0032*** | <<0.0001*** | -- | -- | -- | -- | -- | -- | -- |
| SCMI Low Control | <<0.0001*** | 0.5488 | <<0.0001*** | <<0.0001*** | <<0.0001*** | -- | -- | -- | -- | -- | -- |
| SCMI High Treatment | <<0.0001*** | 0.6885 | 0.0005*** | 0.0043*** | <<0.0001*** | 1.0000 | -- | -- | -- | -- | -- |
| SCMI High Control | <<0.0001*** | 0.0156* | <<0.0001*** | <<0.0001*** | <<0.0001*** | 0.1250 | 0.2500 | -- | -- | -- | -- |
| OXOC Low Treatment | <<0.0001*** | 0.0173* | 0.2100 | 0.8480 | <<0.0001*** | 0.0028*** | 0.0391* | <<0.0001*** | -- | -- | -- |
| OXOC Low Control | <<0.0001*** | 0.0156* | <<0.0001*** | <<0.0001*** | <<0.0001*** | 0.1250 | 0.2500 | 1.0000 | <<0.0001*** | -- | -- |
| OXOC High Treatment | <<0.0001*** | 0.0002*** | 0.8506 | 0.3661 | 0.0009*** | <<0.0001*** | 0.0018*** | <<0.0001*** | 0.3833 | <<0.0001*** | -- |
| OXOC High Control | <<0.0001*** | 0.0156* | <<0.0001*** | <<0.0001*** | <<0.0001*** | 0.1250 | 0.2500 | 1.0000 | <<0.0001*** | 1.0000 | <<0.0001*** |

## HYDROLOGY

Water levels in upper Halstead Meadow indicate that the bulk of annual discharge occurs as snow melt from mid-March through early July, with a peak in May-June (Figure 7). A few large rain events produced large, but short-lived discharge peaks and rises in the water table. When the Upper Halstead inlet and outlet data overlap from mid-May to September 2010, outflow discharge exceeds inflow discharge. The general pattern is similar in Lower Halstead Meadow (Figure 8) but with a deeper water table that never reached the ground surface. In Upper Halstead water flowed above ground from mid-November 2010 to mid-July 2011 and was within the top 20 cm of soil for most of the remaining time. Water level in Upper Halstead was measured at well 13, adjacent to the large restoration project boundary that filled in a deep erosion gully in 2007. An even larger erosion gully remains unrestored in Lower Halstead Meadow adjacent to well 73. Distinctive in Lower Halstead hydrograph are three separate inflows feeding one outflow, making it difficult to estimate inflow magnitude relative to outflow magnitude.

For calculating a water balance for Lower and Upper Halstead meadows, the time period from August 21st through September 22nd 2010 was selected because all necessary data (inputs, outputs, and water levels) are available, no significant precipitation occurred, and no snow or snow-melt runoff occurred. The calculated water balance for Upper Halstead is shown as the red line in Figure 9. It is the sum of the inflow, outflow and change in storage. Similarly, the water balance for Lower Halstead is shown in Figure 10, with three input flows instead of Upper Halstead's one.

The calculated water balance for the upper and lower portions of Halstead Meadow indicated a residual diurnal fluctuation producing an output that peaked at midday. We interpret this to be the signal of ET from the meadow which we did not measure or calculate. The signal of diurnal fluctuation in surface water input is thought to be the result of upper watershed ET reducing flow during midday. Outflows also show the diurnal variance as does the change in storage. When these are summed the water balance retains a residual diurnal fluctuation that likely is daily ET variance in the meadow. Therefore, we estimated daily ET based on daylight hours, air temperature, and scaled to an amplitude to approximate the diurnal residuals in the water balance. Estimated ET (an outflow and thus a negative value) was then added to the water balance to produce a final water balance that we term "unaccounted" discharge (Figures 11 and 12).

In Upper Halstead Meadow estimated peak daily ET ranges from approximately -2 to -4 L/s and adding these values to the water balance results in unaccounted flows of approximately -4 L/s (Figure 11). Thus Upper Halstead contains 4 L/s more outflow (after accounting for ET and change in storage) than inflow, and we interpret this as groundwater inflow that we did not measure. There are two known groundwater discharge zones in Upper Halstead, and these plus any unknown groundwater flows could be the sources of unaccounted inflow.

In Lower Halstead Meadow estimated peak daily ET ranged from approximately -3 to -6 L/s and adding these values to the water balance produces unaccounted flows ranging from 0 to 3 L/s (Figure 12). This suggests that the water balance including estimated ET contains 0-3 L/s more inflow than outflow. This excess inflow may leave Lower Halstead as groundwater flow around the check dam weir.

Measurements of ET are often expressed in mm/day and we converted our ET estimates from L/s to mm/day. From the Upper Halstead water balance we calculated an average 24-hour ET rate of 0.873 L/s from a 2.26 hectare area, equating to 3.34 mm/day. For the Lower Halstead water balance we calculated an average 24-hour ET rate of 1.319 L/s from a 2.46 hectare area, yielding 4.63 mm/day. These estimates are reasonable for evapotranspiration from a mountain meadow.

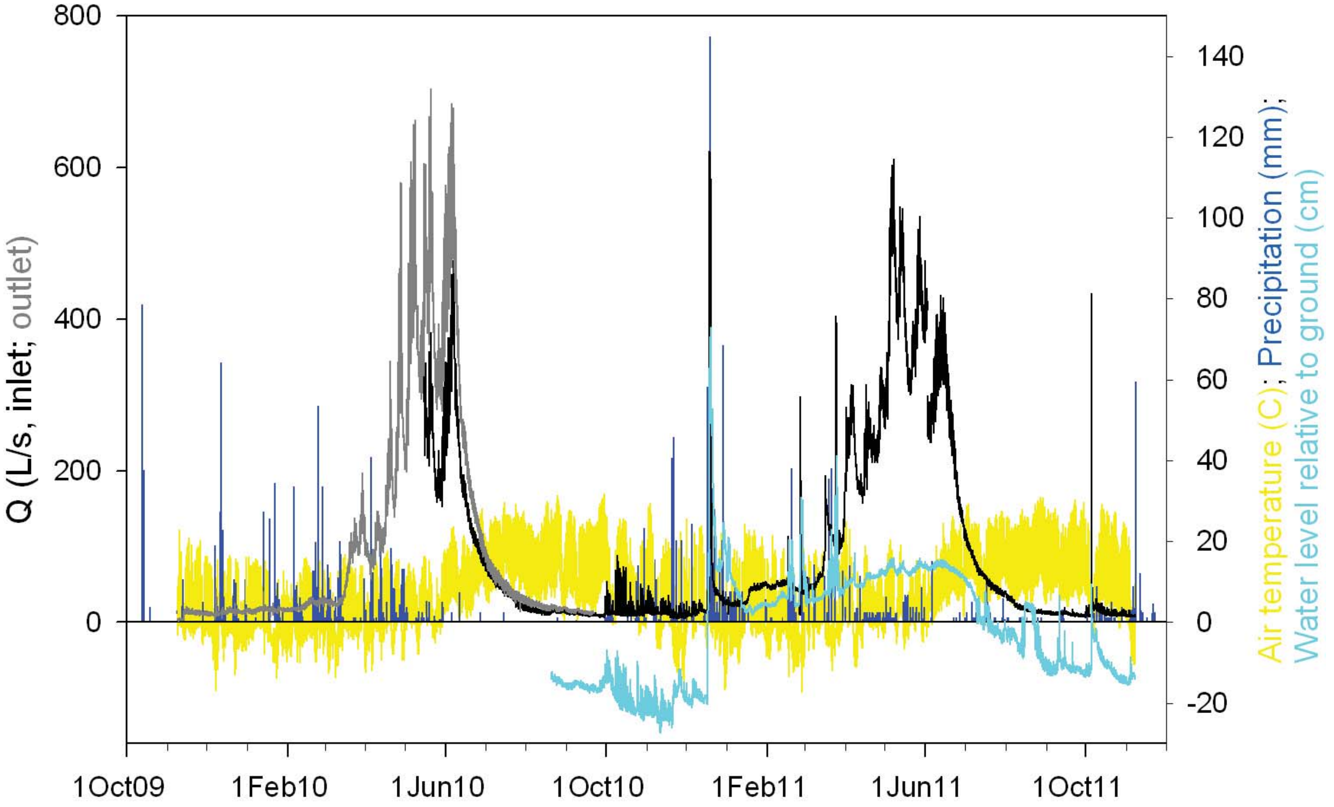

*Figure 7. The hydrograph of Upper Halstead Meadow showing inlet (black) and outlet (gray) flows along with water table depth (light blue), precipitation (blue), and air temperature.*

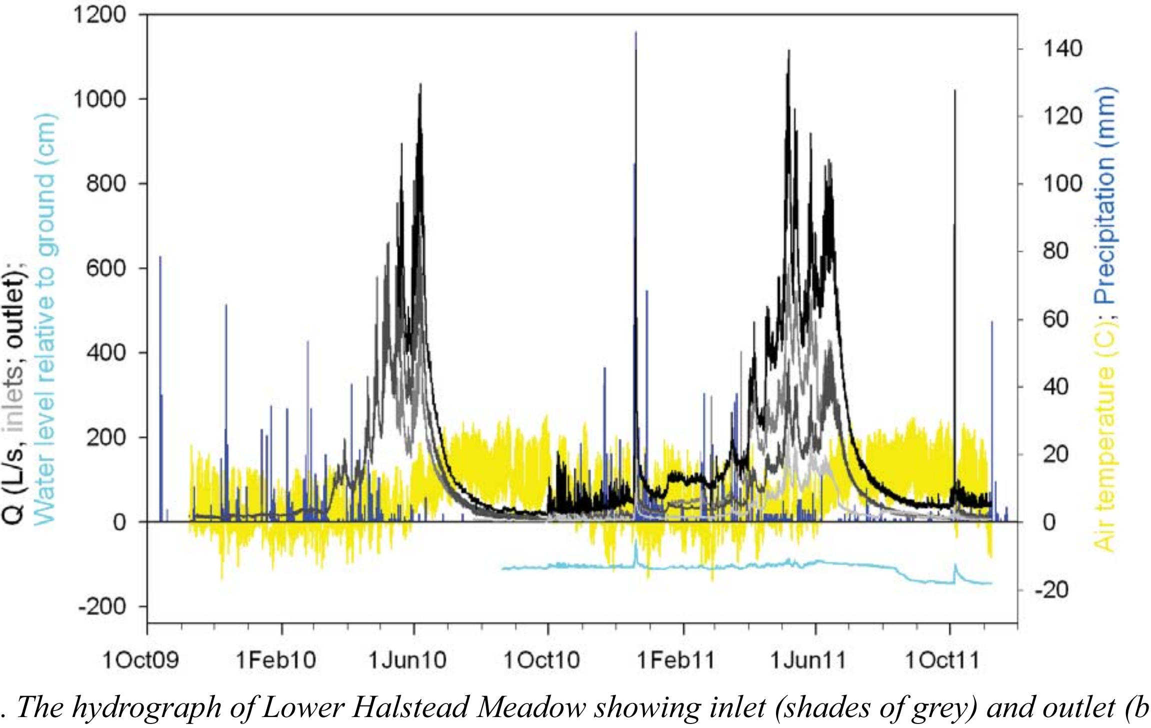

*Figure 8. The hydrograph of Lower Halstead Meadow showing inlet (shades of grey) and outlet (black) flows along with water table depth (light blue), precipitation (blue), and air temperature.*

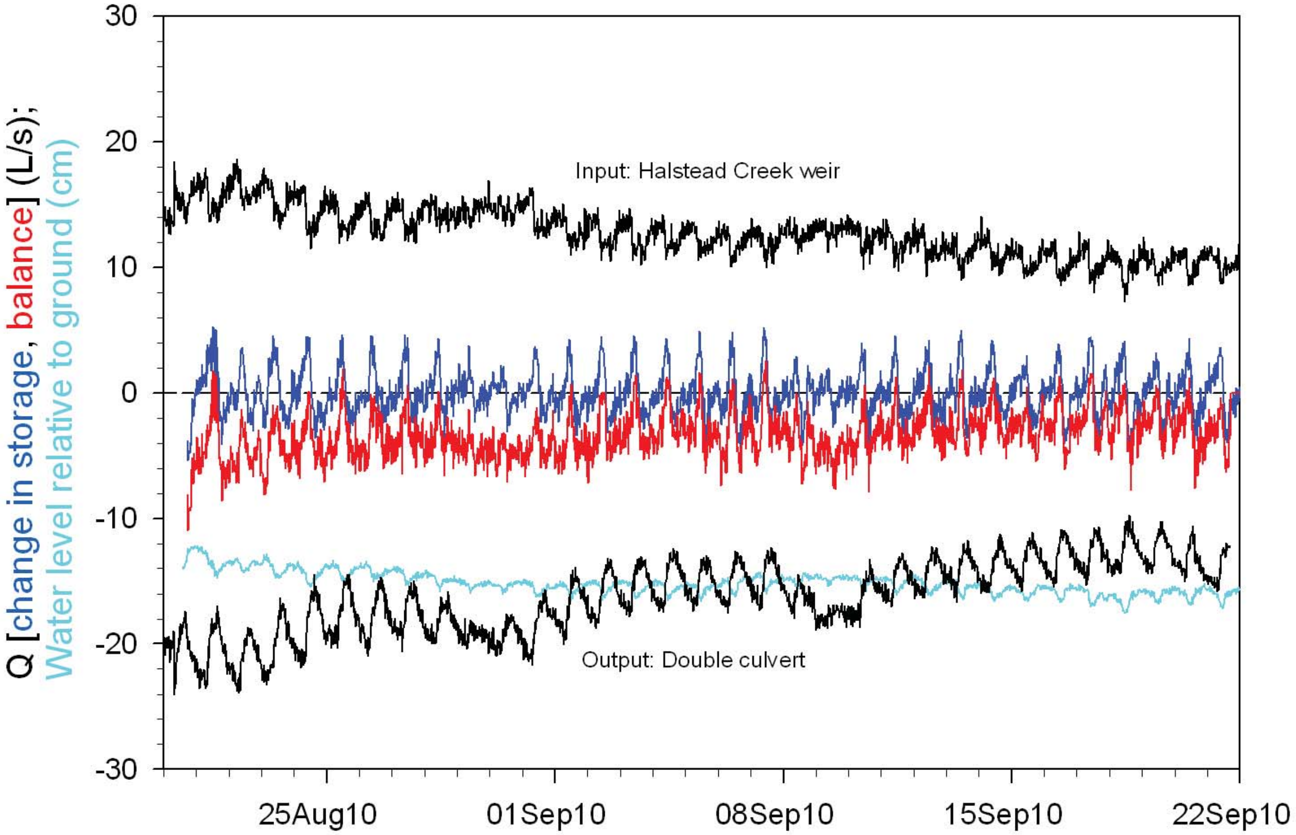

*Figure 9. The water balance for Upper Halstead Meadow. The input (top black line), output (lower black line), and change in storage (blue) were summed to generate the balance (red) of directly measured components. The directly measured water level in well 13 is shown in light blue.*

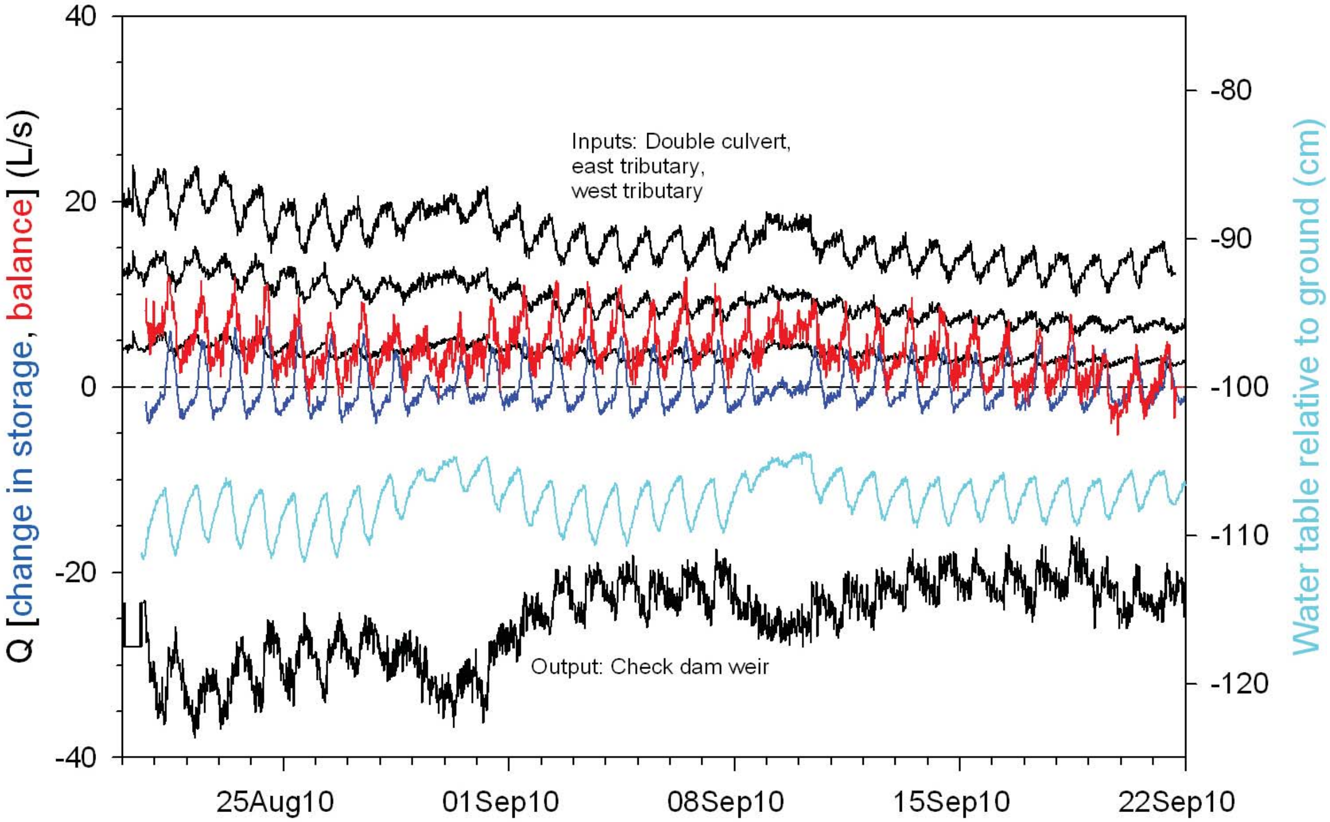

*Figure 10. The water balance for Lower Halstead Meadow. The input (top black lines), output (lower black line), and change in storage (dark blue) were summed to generate the balance (red) of directly measured components. The directly measured water level in well 73 is shown in light blue.*

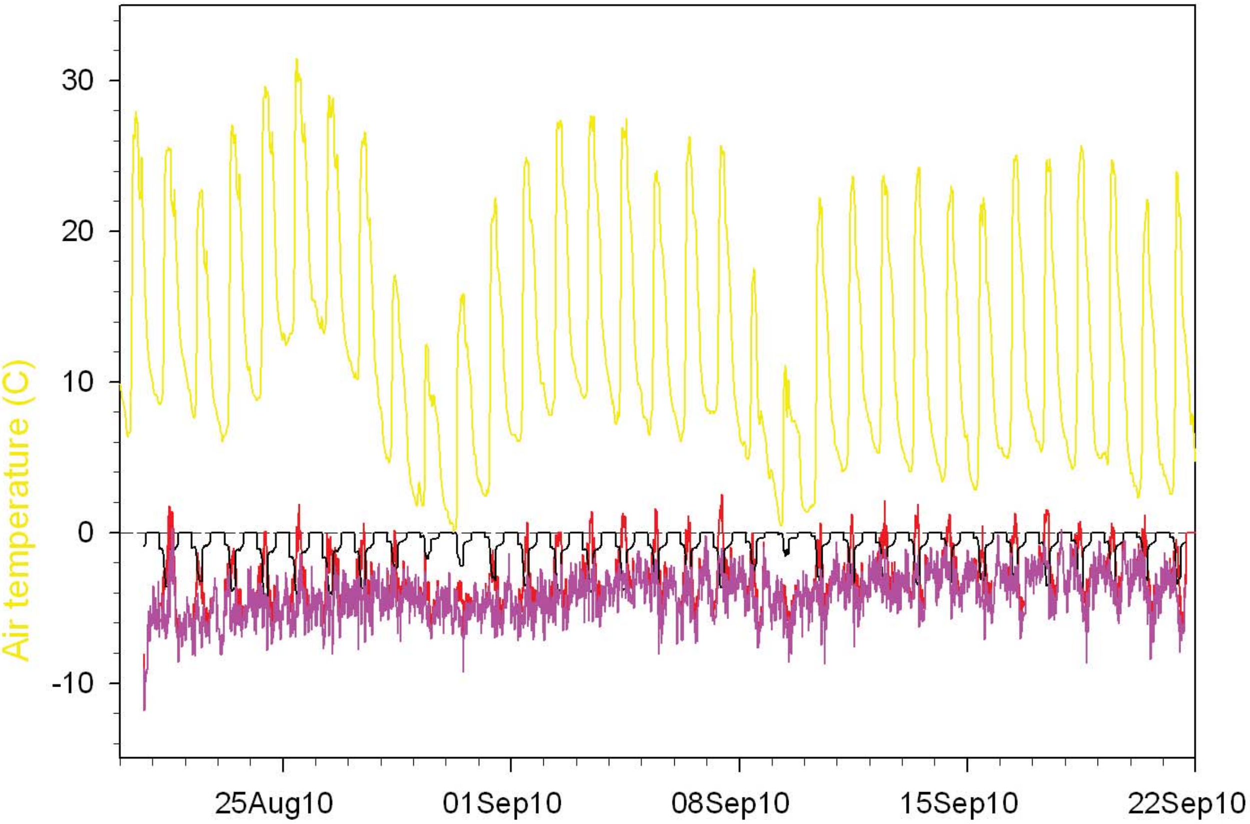

*Figure 11. Estimated evapotranspiration (black) in Upper Halstead was added to the water balance (red) to yield the unaccounted residual flow (purple) attributed to groundwater.*

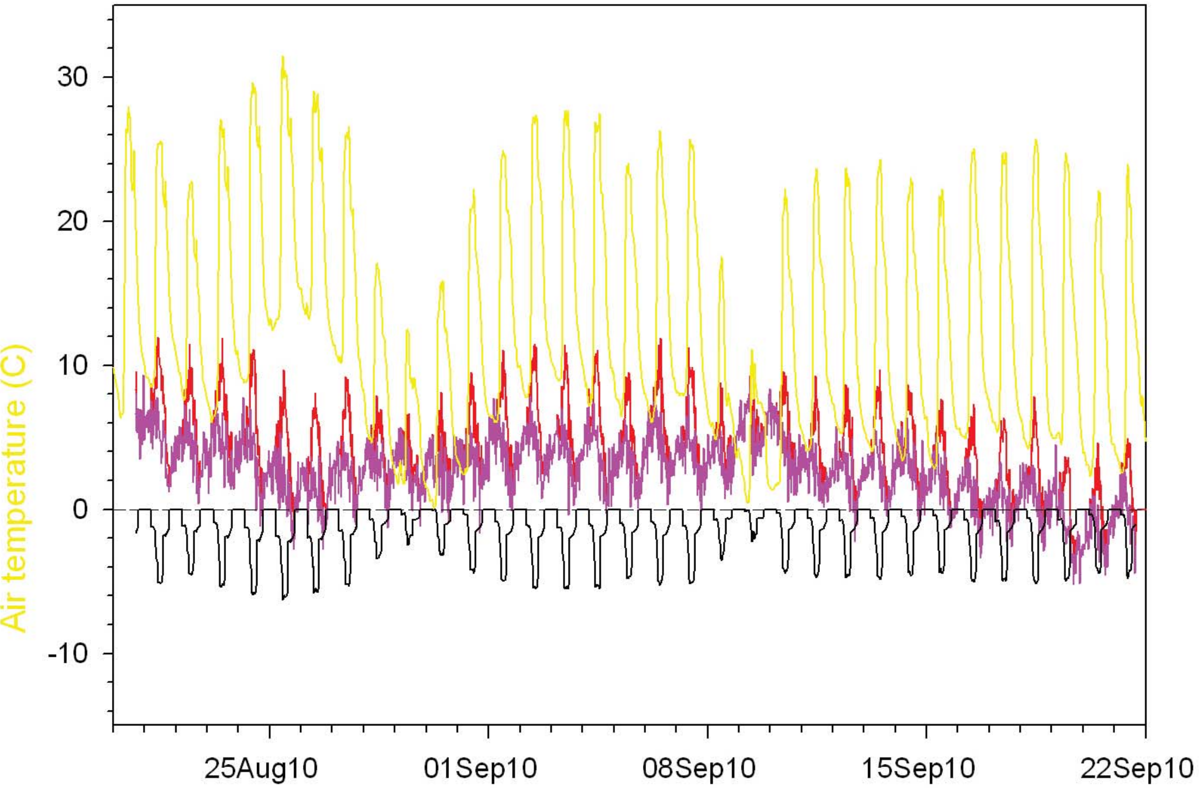

*Figure 12. The estimated evapotranspiration (black) in Lower Halstead was added to the water balance (red) to yield the unaccounted residual flow (purple) attributed to groundwater.*

We also calculated ET using a method that employs the water level data to estimate ET and groundwater recharge rates based on the slopes of diurnal water table draw down and recovery, respectively. See Loheide (2008) for a complete description of the method. We identified 3 time periods during peak plant biomass, peak summer heat, with no precipitation, and no snow melt influence to calculate evapotranspiration. Two of these time periods, August 24-28 and September 1-8, 2010, overlap with the water balance time period and allow for a direct comparison of these methods. The third time period was August 28 – September 6, 2011 and provides an inter-annual comparison. For all calculations here and in the water balance method, above, we estimated a readily available specific yield (Sy) of 0.26 based on our field observations of the near-surface soil at well 13. There is a direct relationship between Sy and ET, e.g. halving the value of Sy will halve the value of ET.

The overall linear trend of the water level data from August 24-28 2010 has a slope of -0.06829 cm/day and the calculated average nighttime groundwater recharge rate was 0.6368 cm/day for a loamy sand (Sy = 0.26). The average ET for the entire 4-day time span was 0.478 cm/day (4.78 mm/day) with a daily minimum (27Aug2010) of 0.415 cm/day and daily maximum (26Aug2010) of 0.540 cm/day. All ET occurred during the daylight hours when sunlight directly hits the meadow, shown as gray hashing in Figure 13.

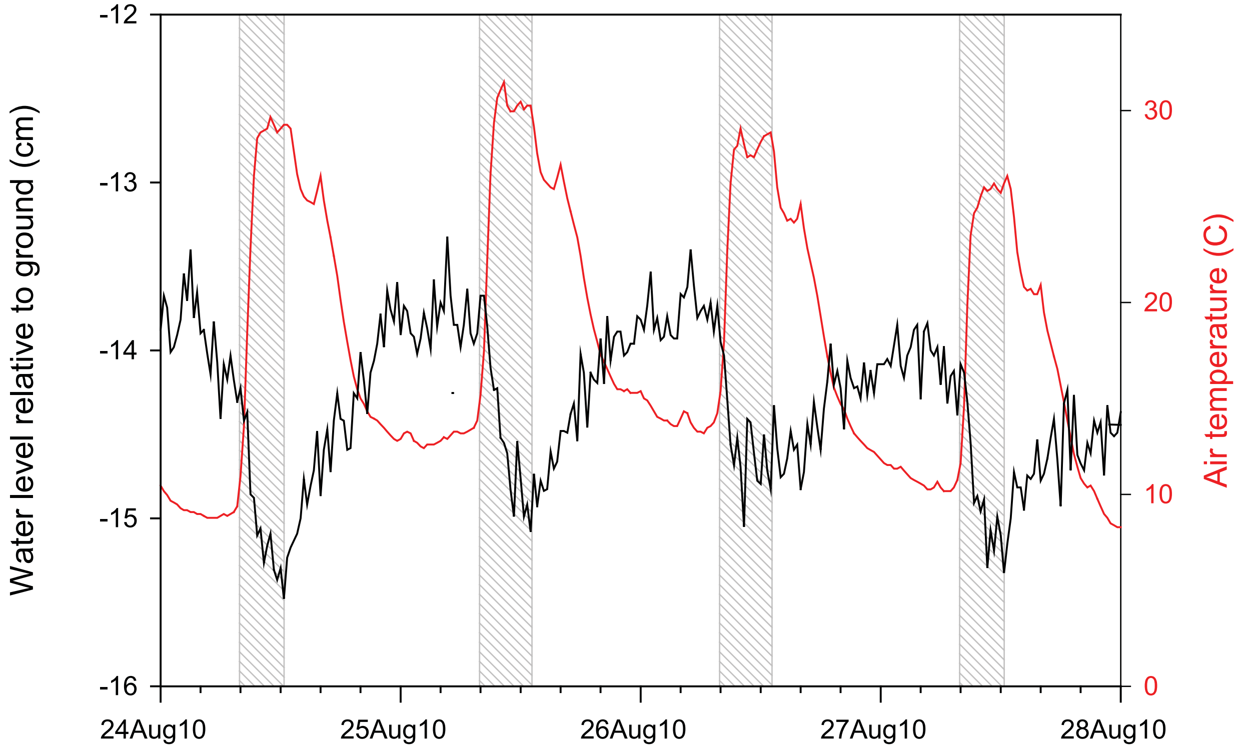

*Figure 13. The water level at well 13 (black) and air temperature (red) in Upper Halstead Meadow for 4 days in late-summer 2010. The gray hashing indicates the time periods of evapotranspiration when water levels are drawn down by plant water use. These draw downs and subsequent recoveries were used to calculate daily evapotranspiration.*

The overall linear trend of the water level data from September 1-8 2010 has a slope of 0.0727 cm/day and the calculated average nighttime groundwater recharge rate was 0.5835 cm/day for a loamy sand (Sy = 0.26). The average ET for the entire 7-day time span was 0.345 cm/day (3.45 mm/day) with a daily minimum (5Sept2010) of 0.109 cm/day and daily maximum (2Sept2010) of 0.465 cm/day. All ET occurred during the daylight hours when sunlight directly hits the meadow, shown as gray hashing in Figure 14.

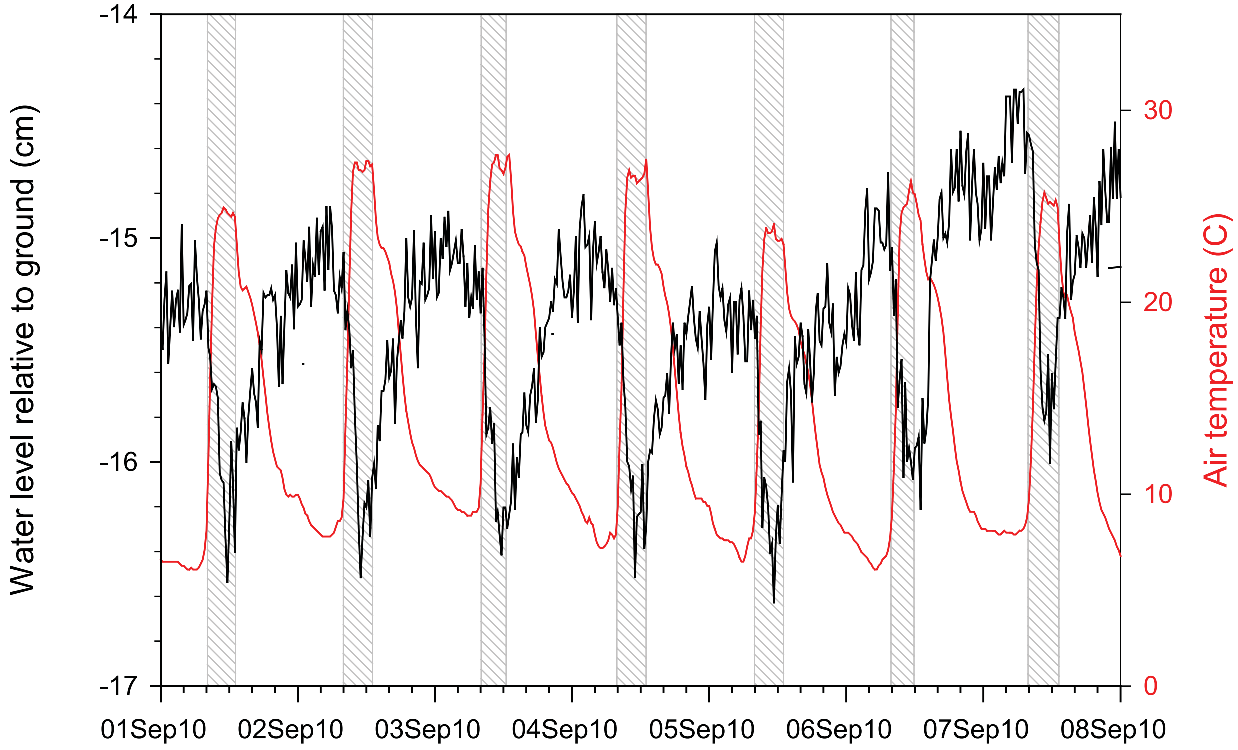

*Figure 14. The water level at well 13 (black) and air temperature (red) in Upper Halstead Meadow for 7 days in late-summer 2010. The gray hashing indicates the time periods of evapotranspiration when water levels are drawn down by plant water use. These draw downs and subsequent recoveries were used to calculate daily evapotranspiration.*

The overall linear trend of the water level data from August 28 – September 6 2011 has a slope of -0.4177 cm/day and the calculated average nighttime groundwater recharge rate was 1.858 cm/day for a loamy sand (Sy = 0.26). The average ET for the entire 9-day time span was 1.274 cm/day (12.74 mm/day) with a daily minimum (4Sept2011) of 0.959 cm/day and daily maximum (29Aug2011) of 1.707 cm/day. All ET occurred during the daylight hours when sunlight directly hits the meadow, shown as gray hashing in Figure 15.

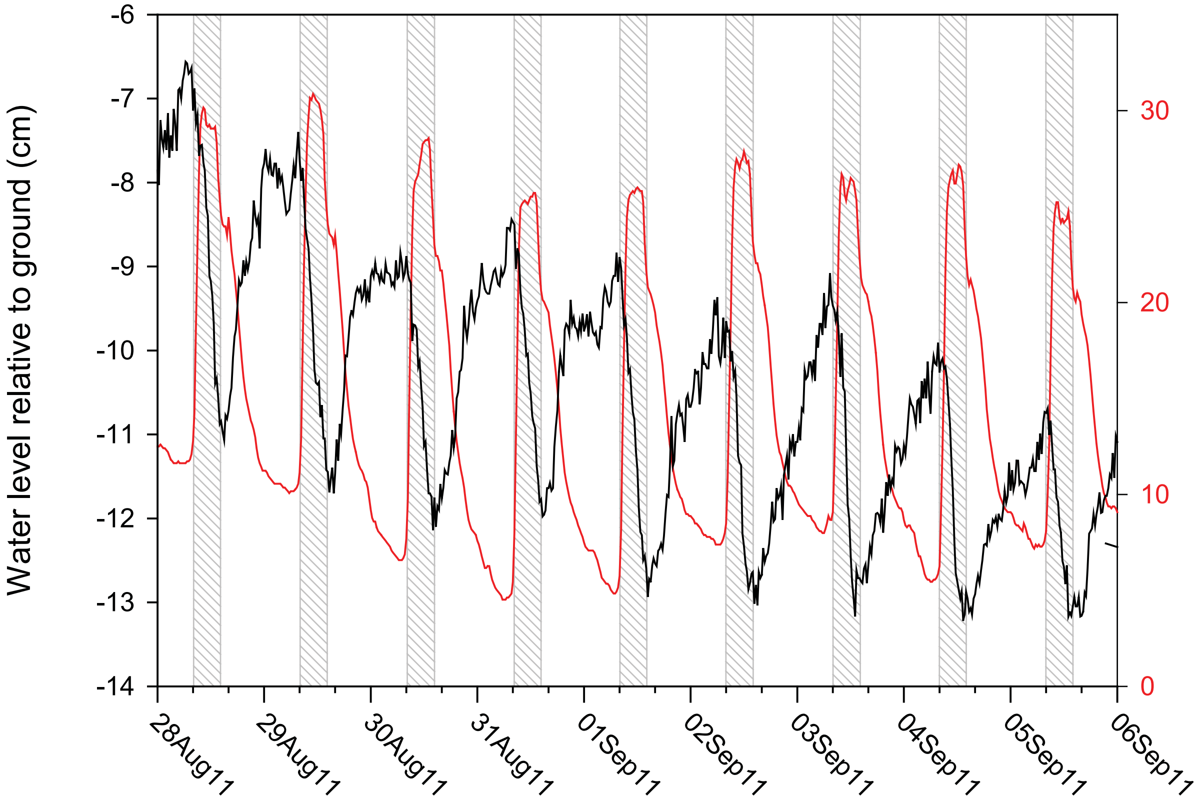

*Figure 15. The water level at well 13 (black) and air temperature (red) in Upper Halstead Meadow for 9 days in late-summer 2011. The gray hashing indicates the time periods of evapotranspiration when water levels are drawn down by plant water use. These draw downs and subsequent recoveries were used to calculate daily evapotranspiration.*

## CONCLUSIONS

There are a number of important findings from this research. First, *Scirpus* growth and spread is negatively correlated with soil compaction. Second, soil compactability can be significantly reduced by the addition of wood chips and/or other organic matter. Third, the success of direct seeding under erosion fabric is species- and flow-dependent. Fourth, peak flows through the meadow can be very high following snow melt and rain events, and evapotranspirative losses and groundwater inputs/losses are each about 10-15% of surface base-flow in magnitude. These results provide important insights for implementing successful wetland restoration and have been used to improve the design restoration for lower Halstead Meadow.

Based on the reduction in plant height and width related to soil compaction, the Lower Halstead restoration plan specifies mixing chipped wood into the fill that is placed in the gully and not driving heavy vehicles over the final grade. This will reduce compaction in the root zone. The factorial experiment using organic matter additions provided data to suggest that 30% addition of wood chips will significantly reduce soil compactability. This value was used for the the Lower Halstead fill mixture.

The seeding experiment demonstrated that *Glyceria elata* has a good (~40%) emergence rate when seeded under the erosion blanket in low flow settings, but a much lower emergence rate (~5%) in high flow sites. A similar pattern, but with lower rates occurred for *Scirpus microcarpus*, with ~12% of seeds emerge in low flow and almost none in high flow sites. *Oxypolis occidentalis* had a ~5% emergence rate in both low and high flow sites. In addition, only *Glyceria* had an appreciable background rate of seedling emergence, with approximately 1 to 5 seedlings emerging for low or high flow plot, respectively. The results of the seeding experiment indicated that seeding in low flow sites could increase the emergence of all three species above background rates, and seeding in high-flow sites increases only *Oxypolis* emergence. Therefore, we recommended seeding all three species across the site, especially in low flow areas, but that seeding should not be relied on to provide plant cover. Because plants are critical to slowing flow and reducing erosive potential, they are most needed in high flow areas where seeding is least effective. We recommend the continued use of live seedling transplants to provide above-ground roughness to slow flow and below-ground roots and rhizomes to bind soil. Seeding may help speed colonization of bare areas between transplants, and *Glyceria* is most effective. Because *Scirpus microcarpus* is the dominant plant within the wetland and provides the most robust above- and below-ground structure to resist flow, establishing it is the primary objective for the Lower Halstead restoration, and this study shows that direct seeding cannot be relied on for this species.

High flows occur frequently during the spring runoff period and following large rain events. Therefore adequate erosion protection is essential for all bare soil surfaces. During construction, surface flow will need to be diverted to dewater the site, and volumes remain high through June, only reaching low flow in August and September. The fluctuating water table in Upper Halstead showed that the restored system has limited storage capacity for inflowing water but provides some buffer for upstream peak flows and maintenance of base flow downstream as the water table declines in late summer. The two methods of estimating evapotranspiration (water balance and water level flux) resulted in very similar values for overlapping time periods in late summer of 2010: 3.34 mm/day by the water balance method and 3.45 mm/day and 4.78 mm/day for two sub-periods by the water level flux method. When applied to a late summer period in 2011, the water level flux method yielded a higher estimate of ET, 12.74 mm/day. Snow melt in 2011 occurred very late, so even though the same calendar period was analyzed in 2010 and 2011, the water level was shallower in 2011 and the plants may have been closer to their peak ET rate.