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THE USE OF HYDROLOGIC AND ECOLOGICAL INDICATORS FOR THE RESTORATION OF DRAINAGE DITCHES AND WATER DIVERSIONS IN A MOUNTAIN FEN, CASCADE RANGE, CALIFORNIA

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Abstract: An intact hydrologic regime and the presence of peat forming vegetation are critical for the persistence of fen wetlands. Fen restoration projects often focus on reestablishing water tables near the soil surface, with little effort directed toward identifying historic hydrologic regimes, hydrologic modifications, and the sources of degradation. We used inconsistencies in the modern hydrologic regime and historic hydrologic indicators present in the soil seedbank, vegetation, and organic soil composition to identify areas of Drakesbad Meadow, a mountain fen in Lassen Volcanic National Park, California, that had been degraded. A network of ground-water monitoring wells and piezometers were used to identify the hydrologic regime of the 4.7-ha site. The presence of thick organic soils in sites with deep late summer water tables, inconsistencies between species present in the seedbank and the existing vegetation, and the presence of dry meadow species such as *Poa pratensis* and *Hordeum brachyantherum* in areas with organic soils were used to determine that 2.4 ha of the site was degraded. A drainage ditch within the fen and diversions of the fen's water supply caused by a road outside of the fen were identified as the source of hydrologic modification and degradation. These were restored by blocking the flow of water in the main drainage ditch and by installing a series of channels to allow water to cross the road. Reconnecting flow beneath the road resulted in raising the summer water table from 80 cm below the soil surface to less than 10 cm in areas downslope of the road. The addition of five sheet-metal dams perpendicular to flow in the main drainage ditch resulted in raising the water table to within 10 to 20 cm of the soil surface in areas adjacent to and down gradient of the ditch. Before restoration, average late August water table levels across the entire site were 30 cm below the soil surface, while average post-restoration water table levels were 19 cm below the soil surface. One year following hydrologic restoration, the percent canopy cover of species indicative of uplands and wet meadows, but not fens including *Deschampsia cespitosa*, *Hordeum brachyantherum*, and *Poa pratensis* decreased compared with pre-restoration years, while the cover of the peat-forming species *Carex utriculata*, *Scirpus microcarpus*, and *Carex simulata* increased. It is clear from our study that fens in this region will not persist under drought-like conditions created by water diversions, yet well-designed restoration projects can be used to restore modified hydrologic regimes and peat-forming vegetation necessary for the persistence of fen wetlands.

Key Words: Drakesbad Meadow, fen hydrology, fen restoration, Lassen Volcanic National Park, mountain fen, organic matter, organic carbon, peatland, peatland hydrology, peatland restoration, seedbank, wetland restoration, wet meadow

INTRODUCTION

Peatland ecosystems form where perennially waterlogged and geomorphically stable soils occur on a time scale of millennia, allowing organic matter to accumulate and form peat soils (Clymo 1983). Two main peatland types occur based on the major sources of water: rain supported bogs and ground-water supported fens (Sjors 1950). Peatlands occur throughout the world, yet may be uncommon in many mountain landscapes due to excessive drainage produced by high relief. Low precipitation and low atmospheric humidity in mountain ranges with continental climates, seasonal dry periods, or high evapotranspiration rates further limit the occurrence of peatlands to sites where bedrock, topography, and landforms allow ground-water discharge to concentrate (Glaser et al. 1997, Almendinger and Leete 1998). Understanding the hydrologic processes that support mountain fens is critical to maintain their high biodiversity of plants (Cooper and Andrus 1994, Cooper 1996, Cooper and Sanderson 1997), amphibians, and invertebrates (Erman and Erman 1975), as well as their proper management and restoration.

Fen formation is controlled by the processes of ground-water recharge and storage, water movement in aquifers, and ground-water discharge into the fen (Siegel 1983, 1988; Wassen et al. 1990; Almendinger and Leete 1998). Fens may be fed by local and/or regional ground-water flow systems, and hydrologic modifications that occur in ground-water recharge areas, along flowpaths, or in discharge zones can affect fen water supplies. Mountain fens often have little water storage capacity due to steep topographic gradients and high ground-water and surface-water flow rates. Water levels respond rapidly to changing inflows or the establishment of preferential flowpaths such as ditches.

Caucasian settlement of the western U.S. altered many hydrologic processes in mountain regions, and many wet meadows and fens were ditched and drained to increase livestock forage production (Cooper et al. 1998). More recent hydrologic modifications have included impacts to fen watersheds including water diversions for local and municipal water supplies, road construction, and ground-water pumping. Hydrologic modifications that lower fen water tables can alter their plant communities (Glaser 1983, Glaser et al. 1990, Fisher et al. 1996, Cooper et al. 1998), soils (Waksman and Purvis 1932, Boelter 1969, Price and Schlotzhauer 1999), carbon balance (Armentano and Menges 1986, Chimner and Cooper 2003a), and net primary productivity (Chimner and Cooper 2003a).

Hydrologic modifications influence the composition of fen plant species and soil properties. A ditch reduced the duration of soil saturation in a southern Rocky Mountain fen, and a native grass species common in seasonally dry mineral soils invaded the dried peat surfaces (Cooper et al. 1998). Mining of mountain fens in this same region reduced species diversity because native species colonized only the wettest portions of these sites, while non-native and upland species colonized drier sites (Cooper and MacDonald 2000). Water diversions also result in dehydration and decomposition of unhumified plant fiber (Chimner and Cooper 2003a), which can lead to a steady decrease in peat thickness and eventually a loss of organic soils (Okrusko 1995). Dehydrated organic soils undergo a change in structure from fibrous to amorphous, may shrink irreversibly, resulting in decreased hydraulic conductivity and increased bulk density (Okrusko 1995, Price et al. 2003). Because plant communities and soil properties are altered by hydrologic modifications, they can be used to identify impacted areas in need of restoration.

Successful restoration of fens must be based upon a thorough understanding of site hydrologic regimes (Wheeler 1995) and the identification of all impacts. Restoration approaches are often site specific and have included blocking and/or filling of ditches, and sealing the edges of a site and pumping water to saturate soils (Cooper et al. 1998, Holden et al. 2004, Wilcox et al. 2006). However, few studies have successfully restored impacts to fen water sources that occur outside of the fen. Once the hydrologic regime has been successfully restored, attention may then focus on revegetation and maintenance of a positive carbon balance. Because propagules of many species can be found in the soil seed bank (Thompson et al. 1997), rewetting can lead to germination and establishment of desirable plant species. If reestablishment is not possible, reintroduction of peat-forming species by seed or seedlings is required (Galatowitsch and van der Valk 1995, Cooper and MacDonald 2000).

Drakesbad Meadow, a 33-ha fen wet-meadow complex was altered by a series of hydrologic modifications both before and after the area was incorporated into Lassen Volcanic National Park, California, in 1958. The present study goals were to identify impacts to Drakesbad Meadow and its watershed by analyzing site hydrologic regime, vegetation composition, and soil types in the meadow and surrounding watershed. We then designed, implemented, and evaluated two projects whose goals were to restore fen hydrologic regime and vegetation.

STUDY SITE

Lassen Volcanic National Park (LVNP) encompasses the southernmost Cascade volcano field and contains a number of active geothermal areas. The glacially carved Warner Valley is the eroded center of the Mount Dittmar volcano (2,000 ka), and contains both Dittmar andesite flows, as well as more recent volcanic and glacial deposits. Drakesbad Meadow (4478053 N, 635067 E), at 1,740-m elevation, is the highest elevation wetland in Warner Valley and the largest wetland in LVNP (Figure 1).

Hot Springs Creek, with a base flow of $\sim$0.7 m^3/s flows along the southern margin of Drakesbad Meadow (Figure 1) and drains into the Upper North Fork of the Feather River. Drakesbad Meadow is

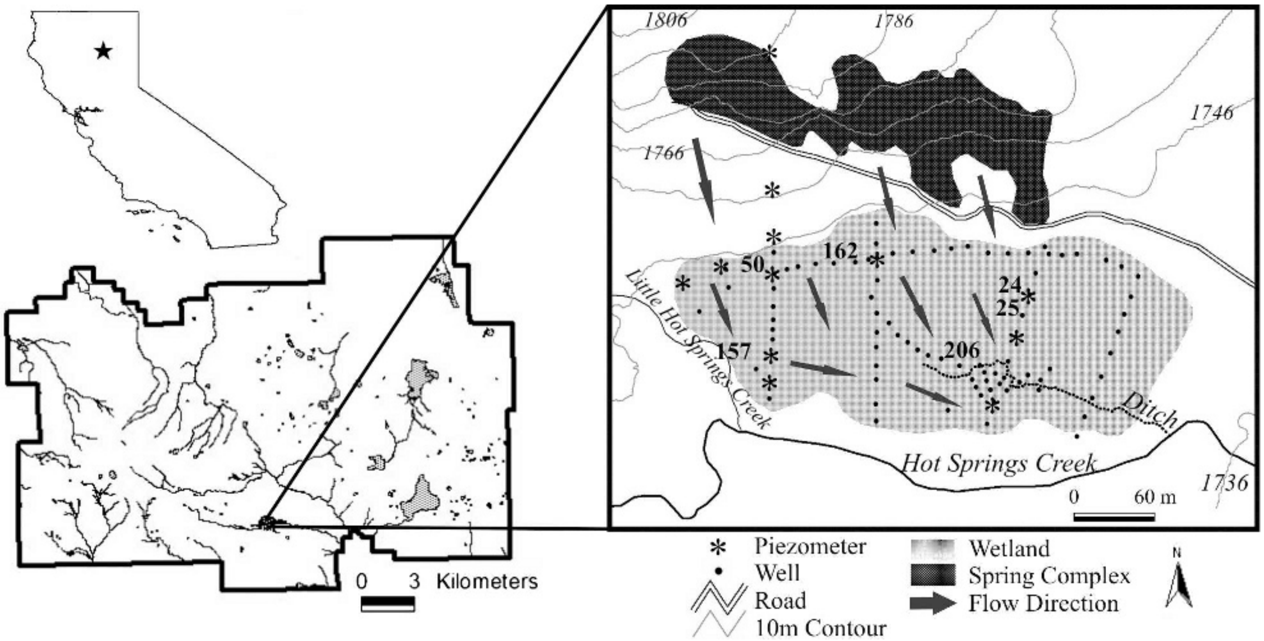

Figure 1. Location of Drakesbad Meadow (right panel) in Lassen Volcanic National Park (bottom left panel), California. Site map (right panel) shows site topography, ground-water discharge and wetland areas, major flowpaths, ground-water monitoring wells, piezometer nest locations, and soil carbon sampling sites.

supported by a large perennial ground-water discharge complex from the south side of Flatiron Ridge (Patterson 2005), an 810-ka dacite flow that extends along the length of Drakesbad Meadow and Warner Valley. The spring complex, located 55 m in elevation above the 4.7-ha study area, occurs at the contact between the older Dittmar andesite lava flow and the more recent Flatiron Ridge dacite. The spring complex is the source for Little Hot Springs Creek, with a base flow of ~0.1 m^3/s. Perennial flow from the springs has allowed portions of the meadow to develop into a fen, which in this area have organic soils more than 40 cm thick derived from the *Cyperaceae* species (Figure 1). Organic soils in the southeastern part of the meadow have been ^{14}C aged to 4,200 years BP (White et al. 2001). Hillsides surrounding the meadow support conifer forest dominated by *Abies magnifica*, *Pinus jeffreyi*, and *Calocedrus decurrens*, and at higher elevations by *Tsuga mertensiana* and *Pinus monticola*. *Alnus incana* and herbaceous dicotylendons form the highly productive hillslope vegetation supported by the springs. Plant species nomenclature follows Gillett et al. (1995).

The regional climate features hot, dry summers and cold, wet winters. Mean monthly temperatures range from −3°C to 22°C. The area is subject to a strongly seasonal, snowmelt-driven hydrologic regime. Mean precipitation is ~80 cm/yr, 90% of which falls as snow. Mean late winter (April 1) snow water equivalent (SWE) at the nearby Harkness Flats snowtel site (4430712 N, 668638 E), which occurs at an elevation similar to Drakesbad Meadow, is ~70 cm. Inter-annual variation and the quantity of summer precipitation is very low, and averages ~1 cm/mo in June, July, and August. Winter and summer precipitation totals during this study, 2001–04, were within one standard error (70 ± 3 cm) of the 74-year mean SWE and within one standard error of the 92-year June to August summer rain mean (3.4 ± 0.3 cm) (California Department of Water Resources 2005).

From the late 1800s to the mid-1900s, irrigation and drainage ditches were constructed in Drakesbad Meadow to increase forage production to support domestic livestock. While agricultural uses ceased in the 1950s, the ditches, shown in Figure 1, have continued to intercept surface and ground-water flows, as well as alter the meadow hydrologic regime. In addition, after the inclusion of the Drakesbad area into LVNP in 1958, the park installed a tank to collect water from hillside springs for use at the Drakesbad Guest Ranch, and a road was constructed along the south side of Flatiron Ridge to construct and access the tank (Figure 1). During the course of this study we found that the access road intercepted the flow of water from the springs to Drakesbad Meadow. The road altered the formerly dispersed flow along the meadow's upslope edge by collecting the flow into a few culverts. Because some meadow areas had remained hydrologically connected to the hillslope spring complex, they were ecologically intact and used as reference sites for understanding pre-impact vegetation and hydrologic regime.

METHODS

Field Analyses

Hydrology. Two direct reading rain gauges were installed at Drakesbad Meadow during each summer of this study and precipitation totals recorded for each event. A network of 87 ground-water monitoring wells and 12 piezometer nests adjacent to wells were used to measure water table depth and vertical gradients in the central portion of Drakesbad Meadow (Figure 1). Wells were hand-augered through the soil profile, fitted with 3.8-cm-diameter fully slotted PVC pipe, and capped at the bottom. Where surface water was present, auger holes were sealed at the surface using native clays to prevent water from entering the well casing. Nests of two or three shallow piezometers were installed adjacent to ground-water monitoring wells within the wetland and in a transect on the slope north of the wetland (Figure 1). Piezometers adjacent to monitoring wells were constructed of 1.0 cm outside diameter PVC Schedule 40 pipe open only at the bottom and pushed to the desired depth with a steel rod inserted to fill the open portion of the pipe. When the pipe was at the desired depth, the steel rod was removed. Piezometers installed on the slope north of the wetland were constructed of 5-cm diameter, 90-cm length, schedule 40 stainless steel drive points (Dean Bennett Supply, Denver, Colorado) with a 75-cm length screen that was decreased to 10 cm long by sealing the upper section of screen with plumbing tape. Drive point piezometers were installed using a sledgehammer, with additional pipe lengths added as needed. Ground-water monitoring wells and piezometers were measured using an electronic probe approximately weekly during the summers of 2001–04.

A continuous reading water level recorder was used in seven wells during 2003 to measure the response of ground-water levels to restoration treatments (Global Water WL-15). When the water table dropped below the monitoring well casing, we set the water table elevation at the well bottom. Surface-water flows into and out of the study area were measured using a 2.5-cm throat width portable cutthroat flume (Baski Co. Denver, Colorado). The location and ground surface elevation of all wells, piezometers, and flume locations were surveyed using a total station.

Vegetation and Soil Seed Bank. The percent canopy coverage of each plant species was determined in a 10-m^2 circular plot centered at each monitoring well during 2002 and again in 2004. The soil seed bank composition at 17 well sites was analyzed during 2002. For each site, ten 200-cm^3 soil samples were collected from the top 10 cm of soil within a 1-m radius circle around each well. Living stems and roots were removed manually from each sample and the remaining soil spread into pans. Soils were maintained at saturation until plants germinated and identification to species was possible. Pans with unidentifiable plants in fall 2002 were wintered in a greenhouse at Chico State University, California and returned to Lassen during summer 2003. All species identifications were completed by late summer 2003.

Soils. Soil at each monitoring well was characterized by organic horizon thickness. Percent organic matter and percent organic carbon were analyzed at a subset of sites to guide our classification of other soil pits. Percent organic carbon was determined at four sites (wells 24, 25, 50, and 206; Figure 1) using a LECO 1000 CHN analyzer (Leco Corporation, St. Joseph, Michigan), and percent organic matter was determined by loss on ignition for two sites (wells 157 and 162: Figure 1). We classified a soil horizon as organic if it was composed of greater than ~40% organic matter (Mitsch and Gosselink 2000) or ~18% organic carbon by weight (Soil Conservation Service 1999). Organic soil horizons could be readily identified in the field, and each well site was classified as having $\geq$ 40 cm, $\geq$ 20 to $<$ 40 cm, or $<$ 20 cm of organic horizons in the upper 40 cm of soil.

Identification of Impacted Sites

Photo Analysis. Vertical air photographs from July 16, 1952 (Photo BUY-3K-107, 108), September 1, 1966 (F-11, 12), and June 25, 2003 (Lassen National Park Photo 1-4) were used to document changes in shrub vegetation cover through time in Drakesbad Meadow. The area of shrubs was mapped using stereo photographic pairs and a high quality stereoscope. Polygons were delineated using ArcView 3.2 onto air photos that had been orthocorrected using Erdas Imagine. A 1931 historical ground photograph of the study site was matched in 2004 to clarify changes in shrub vegetation.

Vegetation, Soils, and Hydrology. Modified areas were identified using hydrology, soil, and vegetation data. The goal was to determine which well sites had the expected natural fen conditions of high water tables with thick organic horizons or wet meadow conditions of deeper water tables and thin organic horizons, compared with hydrologically impacted sites with, for example, thick organic horizons but deep water tables. Detrended Correspondence Analysis (DCA) using the computer program PC-Ord version 4.14 (McCune and Mefford 1999) was used to analyze plot vegetation data, produce species and stand ordinations, and compare organic soil thickness and summer water table depth with vegetation patterns. Centroids of common rhizomatous species of *Cyperaceae* that are likely peat formers, as well as meadow species that are indicative of drier conditions, were plotted in the species ordination space. For the stand ordinations, wells were plotted with symbols indicating the thickness of their organic horizon, and mean July 2002 water table depth being less than or greater than 20 cm below the soil surface. Axis 1 DCA ordination scores were correlated with organic horizon depth and mean July water table depth.

Plant communities were classified using the divisive cluster analysis technique TWINSPAN, performed using PC-Ord, and run with the default settings. Communities were mapped with an overlying July 27, 2002, water table map, drawn with ArcView 3.2, using template contours generated by the inverse distance weighting method (IDW). A map identifying areas with organic horizons 0–20 cm, 20–40 cm, and more than 40 cm thick was created using soil data. This map was overlain with the July 27, 2002, water table depth using the approach described prior. The goal of these analyses was to determine whether plant community boundaries matched patterns of water table depth and soil organic horizon thickness.

Seedbank analysis. Inconsistencies between the soil seedbank and plot vegetation were identified by calculating the percentage of species in the seedbank that also occurred in the vegetation during 2002. Impacted sites were hypothesized to have a lower percentage of seedbank species in the modern vegetation than unimpacted sites. Plots were identified as either impacted or unimpacted, using the approach described prior, and the mean percentage of species of impacted and unimpacted sites compared using a one-sided t-test.

Restoration Approaches

Surface flow from the hillslope spring complex to the wetland was reestablished on July 9, 2003, by breaching the water tank access road in 21 locations. Channels across the road were installed where surface flowpaths occurred on the hillslope above the road. This water then flowed down the hillslope and into the wetland. On July 31, 2003, five sheet metal dams were installed to block flow in the largest ditch in the meadow. Dams were placed at topographic high points to facilitate flow from the ditch. The road manipulation was conducted first so that the effects of the road versus ditch could be differentiated.

Post-restoration hydrologic changes were analyzed using late July water table maps showing areas with water tables 0 to $<$ 20, 20 to $<$ 40, and $\geq$40 cm below the soil surface. Water table maps were produced for 2002, 2003, and 2004 using template contours generated by ArcView 3.2 with the IDW method. Late July dates in 2002 are for the pre-restoration period, 2003 is the post-road restoration period, and 2004 is the post-road and ditch restoration period. The timing of water table depth changes following road restoration are illustrated using a contour map depicting the number of days necessary for the water table to rise to within 20 cm of the soil surface. The long-term response of meadow water levels to road and ditch restoration are shown using hydrographs for typical sites at the base of the hillslope and downslope of the ditch blockages during the summers of 2002, 2003, and 2004.

Mean 2002 and 2004 July water table depth was correlated with organic soil horizon thickness to reveal changes in the correlation coefficients that resulted from the restoration projects.

Short-term vegetation changes (2002–04) were determined by comparing the mean percent cover of six wetland indicator species in 2002 to 2004 at 59 sites with a one-sided t-test. We hypothesized that wet meadow and fen species including *Carex simulata*, *Carex utriculata*, and *Scirpus microcarpus* would increase following hydrologic restoration, while facultative wetland and upland plant species such as *Deschampsia cespitosa*, *Hordeum brachyantherum*, and *Poa pratensis* would decrease.

RESULTS

Identification of Impacted Sites

Photo Analysis. Air photos from 1952, 1966, and 2003 showed reductions in shrub canopy cover (Figure 2). In 1952, shrubs covered 2.91 ha, or 61.9%, of the meadow. However, by 1966, shrub cover had declined by 99% to 0.02 ha, 0.4% of the meadow. During the following 39 years shrub cover has increased to 0.12 ha, or 2.6% of the meadow. A historic ground photo taken in 1931 confirms the extent of shrubs occurring in the early twentieth century, and the 2004 photo match shows the

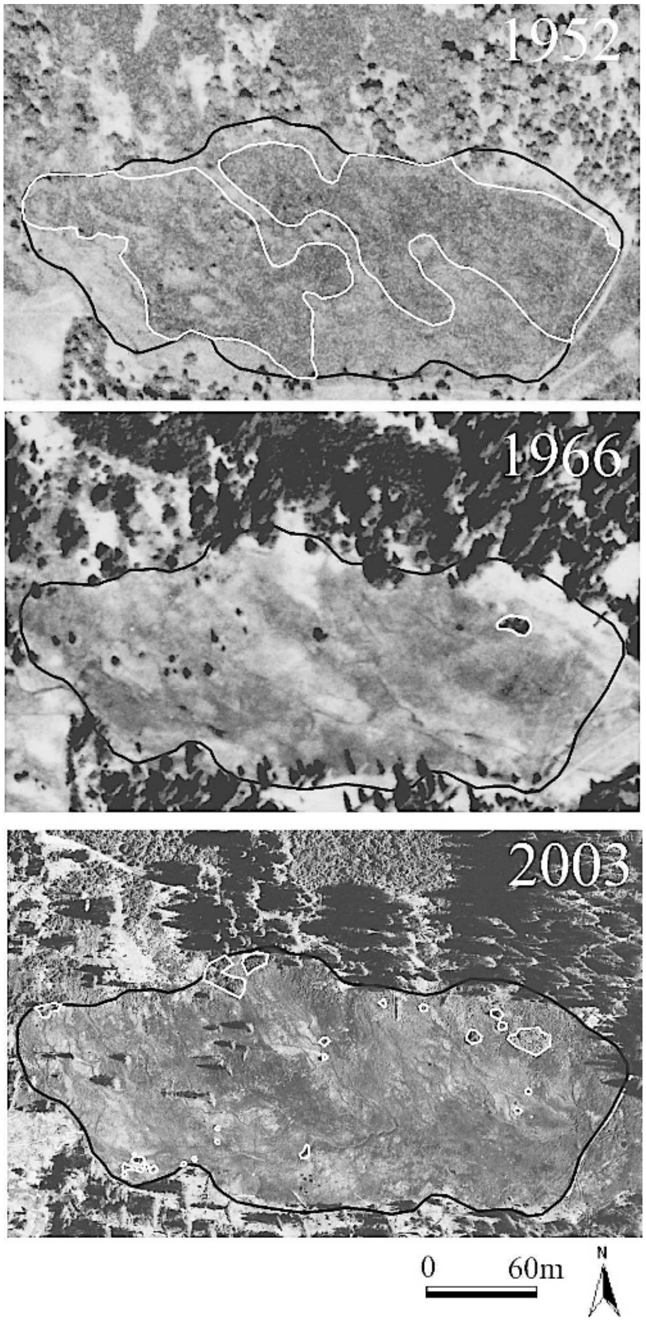

Figure 2. Shrub cover (outlined in white) in 1952, 1966, and 2003 aerial photographs. Wetland area is depicted in Figure 1.

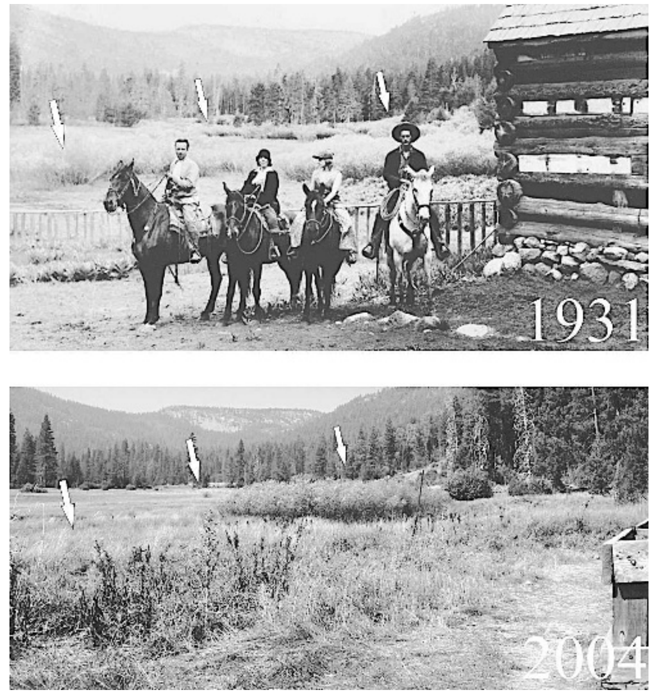

Figure 3. Matched photos from 1931 and 2004. White arrows indicate areas of shrub loss in Drakesbad Meadow. 1931 photo acquired from Bozeman (2005).

current extent (Figure 3). Most shrubs appear to be either *Salix lemmonii* or *Alnus incana* subsp. *tenuifolia*, both of which occur on site.

Soil Seedbank. Thirty vascular plant species emerged from the soil seedbank, including *Carex simulata*, *Carex utriculata*, *Eleocharis pauciflora*, and *Scirpus microcarpus*. For hydrologically impacted sites, a mean of 17.5% (± 6.2) of species in the seedbank also occurred in that site's modern vegetation. By contrast, at sites considered hydrologically intact, a mean of 42.6% (± 14.2) of seedbank species occurred in the modern vegetation. The seedbank and plot vegetation were significantly different ($P = 0.002$) between impacted and unimpacted sites, suggesting that impacted sites have undergone a significant vegetation change.

Vegetation, Soils, and Hydrology. Two to 18 vascular plant species occurred per 10-m^2 plot. Mosses were not present in most plots and were dominant nowhere. DCA of plot vegetation composition data revealed a gradient from stands dominated by obligate wetland species, including *Carex simulata*, *C. utriculata*, *C. nebraskensis*, and *Eleocharis pauciflora* on the left side of the ordination space, to stands dominated by species of wetland margins and uplands such as *Phleum pratense*, *Agrostis giganteusa*, *Veratrum californicum*, and *Poa pratensis* on the right (Figure 4A). Total variance in the ordination was 3.24, the eigenvalue of Axis 1 was 0.56, and 0.28 for Axis 2. Axis 1 of the plot ordination was negatively correlated with organic horizon thickness, $r = 0.50$ (Figure 4B). Sites with organic soil horizons greater than 20 cm thick generally occurred on the left side of the ordination space, while sites with organic horizons less than 20 cm occurred on the right. Axis 1 was also correlated ($r = 0.37$) with mean July 2002 water

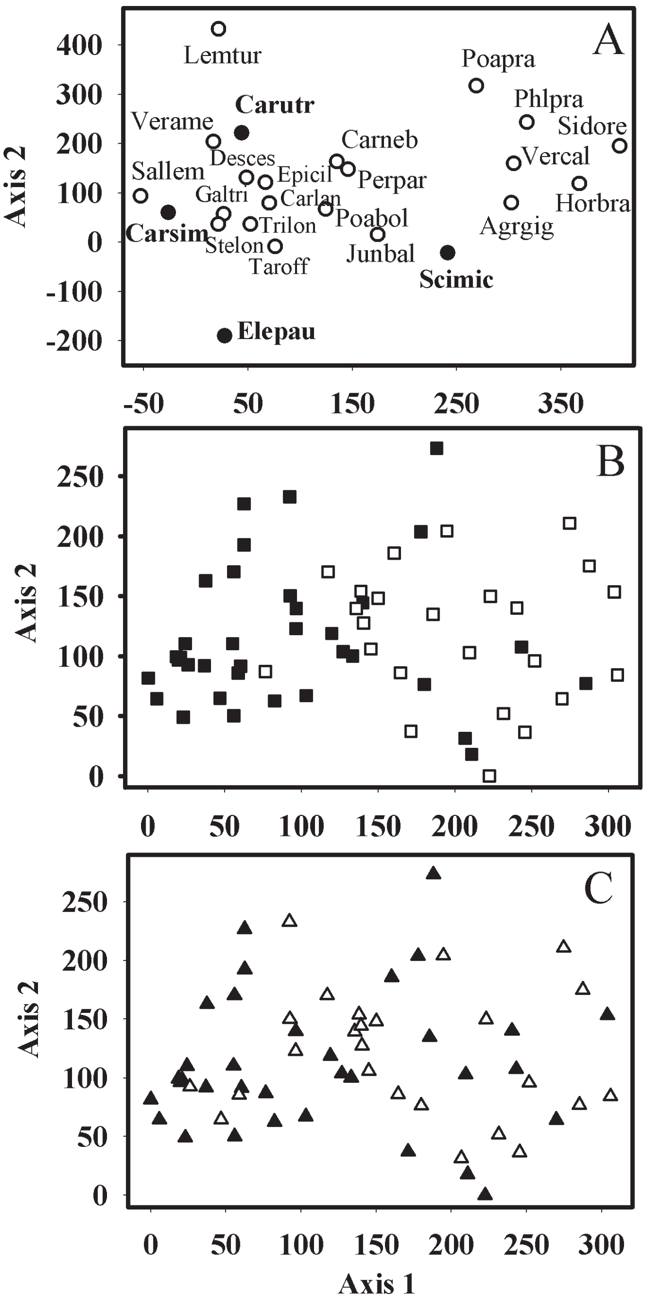

Figure 4. A. DCA species ordination illustrating the centroids for (○) non peat-forming species: *Agrostis gigantea* (Agrgig), *Carex lanuginosa* (Carlan), *Carex nebraskensis* (Carneb), *Deschampsia cespitosa* (Desces), *Epilobium ciliatum* (Epicil), *Galium trifidum* (Galtri), *Hordeum brachyantherum* (Horbra), *Juncus balticus* (Junbal), *Lemna turionifera* (Lemtur), *Phleum pratensis* (Phlpra), *Poa bolanderi* (Poabol), *Poa pratensis* (Poapra), *Perideridia parishii* (Perpar), *Salix lemmonii* (Sallem), *Sidalcea oregana* (Sidore), *Stellaria longipes* (Stelon), *Taraxacum officionale* (Taroff), *Trifolium longipes* (Trilon), *Veratrum californicum* (Vercal), *Veronica americana* (Verame), and (●) peat-forming species: *Carex simulata* (Carsim), *Carex utriculata* (Carutr), *Eleocharis pauciflora* (Elepau), and *Scirpus microcarpus* (Scimic). B. DCA ordination illustrating plots with (■) > 20 cm organic soil and (□) 0–20 cm organic soil. C. DCA ordination illustrating plots with a mean 2002 July water table depth (▲) of 0–20 cm depth, and (△) > 20 cm depth.

table depth (Figure 4C), although this correlation is not as strong as with organic horizon thickness. When correlated with DCA Axis 1 values, plots with a mean water table near the soil surface in July 2002 had a higher correlation (r = 0.51) than plots with deeper mean July 2002 water table depths (r = 0.11). Sites with water tables inconsistent with stand vegetation and organic soil thickness indicated an altered hydrologic regime.

Percent organic carbon and percent organic matter varied both between sites and with depth below the ground surface (Tables 1, 2). For example, at site 24 the highest percent organic carbon occurred at 35–55-cm depth, while at site 206 it was highest at 20–38-cm depth. Sites 24 and 50 had greater than 30% organic carbon at 40-cm depth, while site 206 had greater than 16% organic carbon at 40-cm depth. Site 162 had greater than 34% organic matter at 27–37 cm.

Approximately 2.6 ha, or 55% of the wetland, had organic horizons more than 20 cm thick, ~2.1 ha had organic horizons 20–40 cm thick, and 0.5 ha had greater than 40 cm thick organic horizons. Approximately 10% of the Drakesbad Meadow study area had organic soils that would meet the criteria to be classified as histosols according to NRCS (Soil Conservation Service 1999), and large areas had histic epipedons, with organic soil horizons greater than 20 cm but less than 40 cm thick. Areas with the thickest organic horizons occurred near the base of Flatiron Ridge where water from the spring complex flowed into the meadow.

Approximately 17% (0.8 ha) of sites with organic horizons greater than 20 cm thick, and 30% of the area with organic soil horizons greater than 40 cm thick had a late summer water table more than 20 cm below the ground surface (Figure 5A). It is unlikely that these water table depths could have allowed organic horizon formation (Chimner and Cooper 2003b), and these areas were identified as hydrologically impacted by either the water tank road or ditches within Drakesbad Meadow.

Piezometric data indicated that little to no vertical gradient existed within the organic layer in Drakesbad Meadow. A small vertical gradient occurred within fine textured mineral layers underlying the organic layer, but upward flows would be too small

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Table 1. Percent organic carbon at different soil depths for sites 24, 25, 50, and 206 in Drakesbad Meadow. See Figure 1 for site locations.

24		25		50		206	
Depth	% C	Depth	% C	Depth	% C	Depth	% C
0–10	31.6	10–20	32.3	10–20	31.3	10–20	33.2
10–25	38.4	20–30	15.3	20–30	24.9	20–38	26.2
25–35	39.4	30–40	5.7	30–40	32.2	38–45	16.2
35–45	44.1	40–50	4.8	40–45	15.1		
45–55	44.0						

to support the water table within the organic soils. The lack of vertical gradient confirmed the importance of the hillslope spring complex as the main source of water supporting Drakesbad Meadow.

Four plant communities dominated by two species were identified with TWINSPAN: *Carex simulata* - *Carex utriculata*, *Carex nebraskensis* - *Deschampsia cespitosa*, *Poa pratensis* - *Hordeum brachyantherum*, and *Scirpus microcarpus* - *Veratrum californicum* (Figure 5B). Plant communities corresponded with late 2002 July water table depths. Areas with a late 2002 July water table within 20 cm of the soil surface are dominated by the *Carex simulata* - *Carex utriculata* community and included species that typically occur in peatlands. The *Carex nebraskensis* - *Deschampsia cespitosa* community occupies the seasonally dry area between the two major flowpaths and downslope from the main drainage ditch, and is dominated by species that rarely occur in California fens (Cooper and Wolf 2006). Most wells in this community have organic horizons greater than 20 cm thick, but water table depths more than 20 cm below the soil surface. The *Poa pratensis* - *Hordeum brachyantherum* community occurs primarily on meadow margins and northeastern corner adjacent to a horse coral. The *Scirpus microcarpus* - *Veratrum californicum* community is restricted to a few areas with abundant surface water.

Table 2. Percent organic matter at several soil depths (cm) at sites 157 and 162. See Figure 1 for site locations.

157		162	
Soil Depth	% Organic Matter	Soil Depth	% Organic Matter
0–15	35.6	3–12	67.0
15–25	23.8	12–24	69.0
24–30	7.5	27–37	34.0
30–40	6.1	37–43	15.0

Hydrologic Restoration

Precipitation. Six rain events were recorded at Drakesbad Meadow during June to August 2002, 2003, and 2004, the largest of which was 0.8 cm on August 2, 2003. Low summer precipitation of the

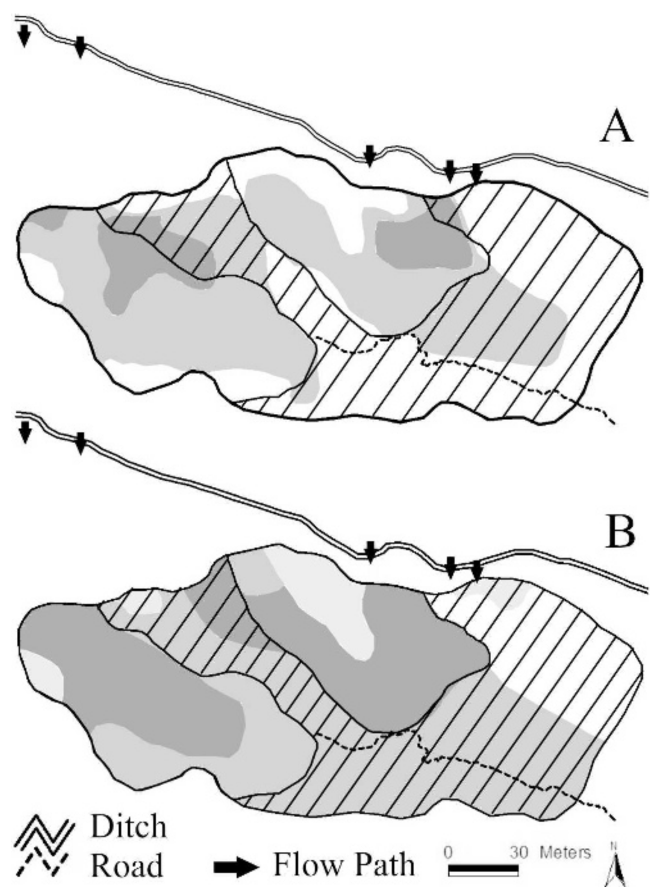

Figure 5. A. Organic soil thickness and water table depth < 20 cm (▨) on July 27, 2002. Organic soil thicknesses are > 40 cm (▩), 20–40 cm (▩), and < 20 cm (□). B. Plant communities and water table depth < 20 cm (▨) on July 27, 2002. Communities are *Carex simulata*/*Carex utriculata* (▩), *Carex nebraskensis*/*Deschampsia cespitosa* (▩), *Poa pratensis*/*Hordeum brachyantherum* (▩), and *Scirpus microcarpus*/*Veratrum californicum* (□).

Drakesbad area and the low variability of discharge from the spring complex allowed for the direct comparison of pre-restoration and post-restoration water levels.

Ground-Water Response. The installation of 21 water bars restored flow across the water tank access road and increased the number of flowpaths to Drakesbad Meadow from five points discharging a total of 2.83 L/s to 21 points discharging 3.67 L/s (Figure 6). The road restoration added ~0.84 L/s (73 m^3/day) of flow into the meadow, equivalent to a water depth across the meadow of 0.15 cm/d. In late July 2002, 2.25 ha of the wetland had a water table within 0–20 cm of the ground surface. This area occurred primarily in two flowpaths that had remained hydrologically connected to the hillslope spring complex due to the inadvertent positioning of culverts when the water tank road was constructed (Figure 6).

Following the road restoration, the water table of a ~0.25 ha area between the two major flowpaths rose to within 20 cm of the ground surface by July 27, 2003 (Figure 6), with areas closest to the road showing a water level rise to near the soil surface within days of project implementation (Figure 7). The water table depth at well A rose from 74 to 7 cm below the soil surface within 24 hours. Wells B–E rewetted in a similar manner during the subsequent nine days, as a ground-water mound developed on the northern edge of Drakesbad Meadow and expanded south and east across the meadow. When the ground-water mound reached the well sites, the water level in each well rose from greater than 70 cm, to less than 10–20 cm below the soil surface within ~12 hours. Wells F and G, which occur at a greater distance from the water source, had a slower water level rise, as well as a diurnal water level variance of up to 10 cm. The highest water table occurred at 0900 and the lowest at 1800 hours, suggesting evapotranspiration-driven diurnal water level changes. Restoration activities reversed late summer water table declines with a rapid rise in water table depth that was maintained the year following restoration (Figure 8A).

Water levels in the southeastern part of Drakesbad Meadow, an area of 2.20 ha, remained greater than 20 cm deep, even in sites with organic soil horizons more than 20 cm thick. This suggested that the ditch's influence on meadow water levels persisted after the road restoration. Following installation of the sheet metal dams to block the ditch on July 31, 2003, ground-water levels rose in the southeastern portion of the meadow. The rise in water table occurred simultaneously with a decrease

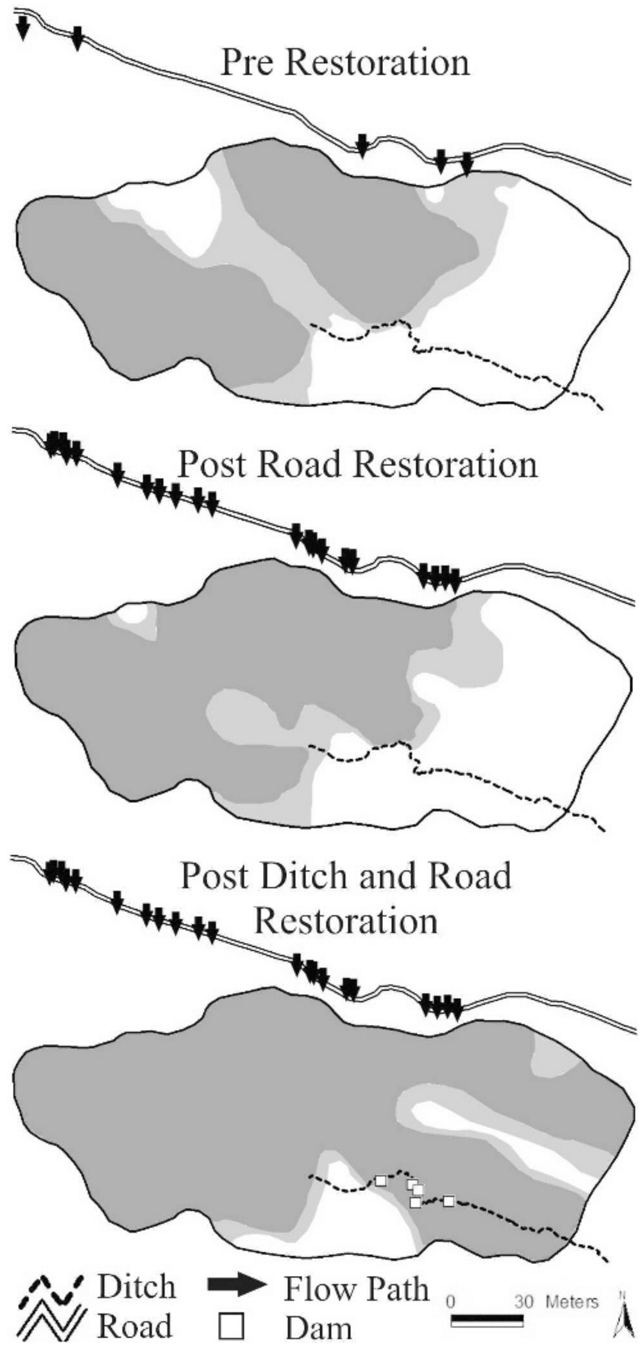

Figure 6. Water table depths pre-restoration (July 28, 2002), post-road restoration (July 27, 2003), and post-road and ditch restoration (July 28, 2004). Water table depths are <20 cm (▒), 20–40 cm (░), and >20 cm (□).

in discharge in the ditch from ~0.79 L/s prior to the installation of sheet metal dams, to ~0.12 L/s after three days and ~0.03 L/s 10 days after ditch blockage. The dispersion of water from the main ditch resulted in the water table rising to the soil surface in much of the southeastern portion of the meadow (Figure 8B), and in July 2004, 3.85 ha, or 82%, of the wetland had a water table within 20 cm

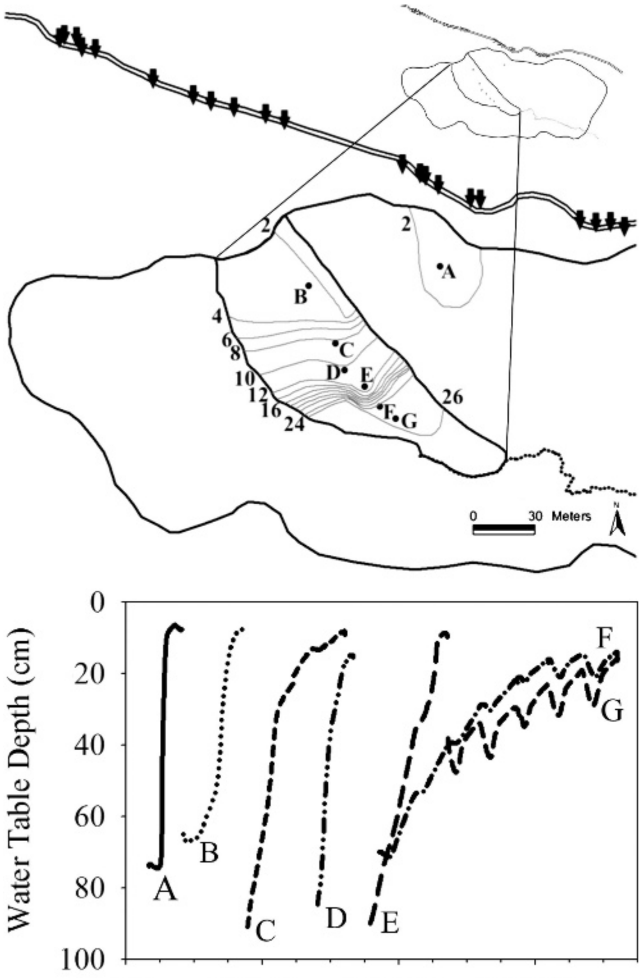

Figure 7. Patterns of wetland re-wetting following road restoration. Contours are time in two-day intervals following the implementation of restoration for the water table to rise to within 20 cm of the ground surface. Graph represents continuous water level data for wells (A–G) following road restoration.

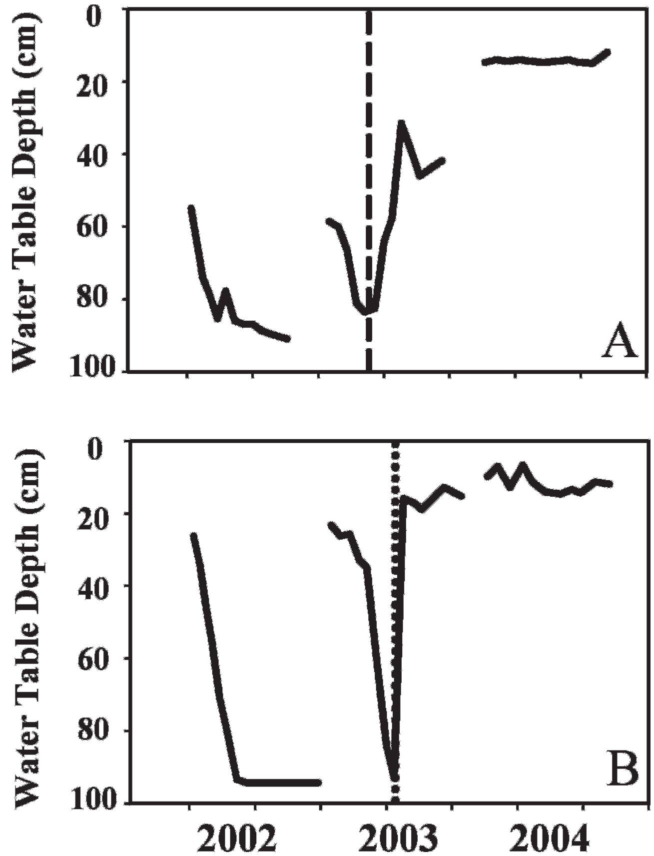

Figure 8. June through August water table hydrographs for 2002, 2003, and 2004 for wells A) downslope of the road and B) downslope of the ditch. Dotted lines indicate the time of road restoration (A, – –) and ditch restoration (B, ---).

of the soil surface, an increase of 1.60 ha, or 71%, from July 2002 (Figure 6). The south meadow area still had a water table greater than 40 cm deep in July 2004 in areas down gradient of the ditch, but up gradient from the influence of the sheet metal dams.

The two restoration projects resulted in higher mean July water table depths in 2004 than 2002. This increased the statistical correlation of organic horizon thickness and water table depth at wells from r = 0.29 to 0.47 (Figure 9). Thus, the post-restoration water tables more closely matched the historic hydrologic conditions necessary to produce thick organic soil horizons.

Vegetation Response. The mean percent cover of *Carex utriculata*, *Carex simulata*, and *Scirpus microcarpus* were higher in 2004 than in 2002, while

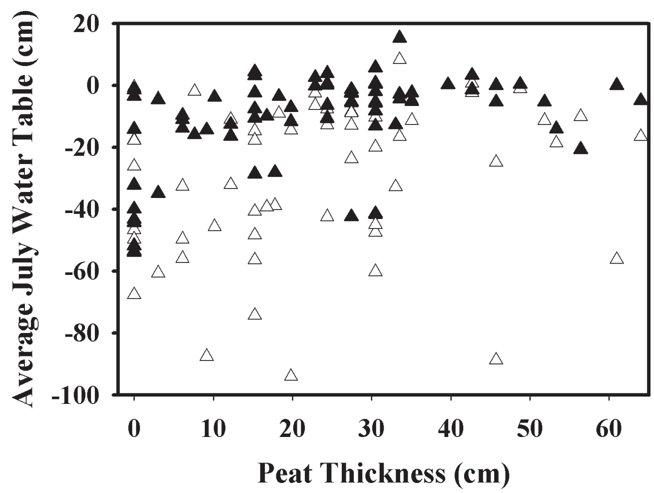

Figure 9. Peat thickness and mean July water table relative to the ground surface of wells during the pre-restoration period of 2002 (○) and the post-restoration period of 2004 (●).

Table 3. Pre-restoration (2002) and post-restoration (2004) percent cover and standard error of *Carex utriculata*, *Carex simulata*, *Scirpus microcarpus*, *Deschampsia cespitosa*, *Hordeum brachyantherum*, and *Poa pratensis* in 59 plots.

	Pre-restoration %	Post-restoration %	P
C. utriculata	12.2 ± 2.3	13.3 ± 2.2	0.158
C. simulate	14.8 ± 2.9	20.2 ± 3.4	< 0.001
S. microcarpus	12.3 ± 2.5	15.5 ± 2.8	0.057
D. cespitosa	1.7 ± 0.6	1.3 ± 0.5	0.047
H. brachyantherum	5.6 ± 1.7	4.7 ± 1.5	0.062
P. pratensis	5.8 ± 1.6	3.0 ± 0.9	0.002

the cover of *Deschampsia cespitosa*, *Hordeum brachyantherum*, and *Poa pratensis* were lower (Table 3). These differences were statistically significant for *Carex simulata* ($P < 0.001$), *Deschampsia cespitosa* ($P = 0.047$), and *Poa pratensis* ($P = 0.002$).

DISCUSSION

Identification of Impacted Sites

The effect of hydrologic modifications, such as ditching, is relatively well documented for peatlands, yet few studies have identified hydrologically modified and intact areas for use in restoration planning (van Diggelen et al. 1994). Hydrologic modifications to ombrotrophic peatlands are typically drainage features within the peatland (Charman 2002), with restoration achieved by blocking the drains (Price et al. 2002), sealing the edges of the site, and pumping in additional water (Wheeler and Shaw 1995, Charman 2002) to reestablish near surface-water tables. The identification of hydrologic modifications in fens is more difficult (Charman 2002) because hydrologic modifications can occur both on-site within the fen in the form of drainage features (Cooper et al. 1998, Richert et al. 2000, Jauhiainen et al. 2002,) and off-site in the form of water diversions (Grootjans and van Diggelen 1995, Chimner and Cooper 2003b) or ground-water extraction (Harding 1993, Fojt 1994). Fen restoration planning must include a diagnostic approach and start with a thorough understanding of the potentially complex ecohydrologic regime (van Diggelen et al. 1994, Grootjans and van Diggelen 1995, Schrautzer et al. 1996, Wassen and Grootjans 1996, Wilcox et al. 2006).

Analyses of soil, vegetation, and hydrologic regime were critical for identifying the disturbed portions of Drakesbad Meadow. The existence of ditches was well known because the land use practices of early Caucasian settlers were documented in oral and written histories (Sifford 1994). However, hydrologically modified areas also occurred up gradient from ditches, suggesting that additional, off-site hydrologic modifications had occurred. The presence of thick organic soils in sites with deep late summer water tables, inconsistencies between species present in the seedbank and the existing vegetation, and the presence of dry meadow species such as *Poa pratensis* and *Hordeum brachyantherum* in areas with organic soil layers were used to identify areas affected by the main drainage ditch and the water tank road.

The water tank road diverted surface and subsurface flow from the main water source that supports the entire wet meadow and fen complex. Road construction in mountain regions commonly uses cut-and-fill techniques (Switalski et al. 2004), which can alter hillslope hydrologic regimes by reducing soil infiltration, concentrating water through road drainage structures, and converting subsurface flow to surface flow (Luce 2002). The road captured and channelized the hillslope flow into specific discharge points, resulting in the dewatering of large areas of Drakesbad Meadow. Following snowmelt runoff, the water table in areas between culverts dropped to well below the soil surface, creating oxidizing conditions. This likely produced high organic matter decomposition rates and allowed the invasion of species that do not naturally occur in fens or wet meadows. These results are consistent with road impacts to the Red Lake Peatland of northern Minnesota, which resulted in the drying of peatland areas downslope from a road, nearly eliminating string-flark patterns, drastically altering vegetation composition, and allowing the invasion of exotic species (Glaser et al. 1981, Wheeler et al. 1983). Since the ditching of Drakesbad Meadow occurred in the early 1900s, yet the road has been in place for only ~40 years, the area downslope of the main drainage ditch has likely sustained greater impacts to organic soils and vegetation than areas influenced only by the road.

Photo and Seedbank Analyses

Historic photos revealed that extensive *Salix* and *Alnus* communities once covered most of the central portion of Drakesbad Meadow. However, no shrub species emerged from our soil seedbank analysis. Previous soil seedbank studies have shown that woody plants may be absent or poorly represented, and *Salix* spp. have very short-lived seeds (Leck 1989). Rossell and Wells (1999) found that low densities of five woody taxa emerged from a seedbank study of a southern Appalachia mountain fen, while only three woody taxa emerged in a similar study of a bog in the same region (McGraw 1987).

The high spatial resolution of aerial photography makes it an important data source for wetland vegetation mapping (Harvey and Hill 2001), and historic air photos can be used to quantify vegetation changes over time (Aaviksoo 1993, Freeman et al. 2003). The 96% decrease in shrub cover from 1952 to 2003 at Drakesbad Meadow suggests that shrubs were directly removed by humans, or declined due to hydrologic modifications. Shrub cover was largely eliminated by 1966, and since some areas of the meadow maintained a high water table, it seems likely that shrubs were removed by humans between 1952 and 1966. *Salix lemmonii* and *Alnus incana* are still present in small patches within the meadow, but little colonization has occurred into the cleared areas.

Despite the absence of woody species, the seedbank of impacted sites had lower similarity to standing vegetation than unimpacted sites, suggesting that vegetation changes have occurred. Several studies have shown that the species composition of a wetland soil seedbank does not necessarily resemble the existing vegetation (Leck 1989, Poiani and Dixon 1995, Hanlon et al. 1998). Hydrologic modifications have been found to decrease the similarity of a soil seedbank to the modern vegetation, as was found in degraded mountain fens of the southern Appalachians (Rossell and Wells 1999). In Drakesbad Meadow, despite the existence of the peat-forming species *Carex simulata* and *C. utriculata* in the seedbank, hydrologic modifications allowed the establishment of *Poa pratensis* and *Deschampsia cespitosa*, grass species common to drier, upland, and seasonally dry meadow sites. *Deschampsia cespitosa* was also an important invader of a ditched fen in the southern Rocky Mountains (Cooper et al. 1998).

Sensitivity of Fens to Hydrologic Modifications

Fens of the southern Cascade range and northern Sierra Nevada range, such as Drakesbad Meadow, receive very little rain from June to August each year, and are extremely sensitive to even small reductions of ground-water inflow. Steep topographic gradients, high potential evapotranspiration, and low atmospheric humidity of mountain landscapes of the interior western U.S. maximize hydrologic outputs and result in a nearly complete reliance on ground-water inputs to maintain soil saturation. Unlike fens of the southern Rocky Mountains, which receive summer rain that helps maintain late summer water tables (Cooper et al. 1998), the Mediterranean climate of California and the southern Cascades makes perennial ground-water inputs critical for maintaining late summer water tables. Fens in northern California, and likely elsewhere in the Sierra Nevada and Cascade ranges of the U.S., are not sustainable under the persistent drought-like conditions caused by water diversions, ground-water abstraction, and drainage features. The management and restoration of site hydrologic regimes is critical for the persistence of disturbed fens. Since most fens of this region occur on public lands and have never been mined or cultivated (de Mars et al. 1996), many retain their native soils and soil seedbank and will respond rapidly to hydrologic restoration.

Hydrologic Restoration

Hydrologic restoration focuses on reestablishing near soil surface-water tables (Holden et al. 2004) critical to peat-forming vegetation and net carbon storage (Chimner and Cooper 2003b) necessary for the persistence of fens. Hydrologic restoration can potentially reverse carbon losses, reverting oxidizing peatlands into carbon sinks (Komulainen et al. 1999, Tuittila et al. 1999).

Rerouting the hillslope ground-water flow system across the road resulted in a 30% increase in flow into Drakesbad Meadow. Most important, this restoration resulted in the redistribution of flows to the entire meadow. These inflows created ground-water mounds that rapidly rewetted areas maintained under summer drought conditions since construction of the water tank road 40–50 years ago.

The sheet metal dams decreased flow in the main drainage ditch and redistributed water into sheet flowpaths that resulted in the water table of effected areas rising to near the soil surface within four to five days. To be most effective, ditch blockage efforts should occur upstream of hydrologically impacted areas to allow water to disperse into all impacted areas. Even though discharge in the main ditch decreased by more than 90% following installation of the sheet metal dams, water still flows around some dams, decreasing their effectiveness (Cooper et al. 1998). While our restoration projects succeeded in reestablishing a near surface-water table over much of Drakesbad Meadow, complete ecosystem restoration must include filling the ditches with soil that would allow vegetation to cover the ditch locations. In addition, all natural hillslope drainage patterns must be restored.

Vegetation Response to Hydrologic Restoration

One year following hydrologic restoration, the canopy cover of upland and dry meadow species *Deschampsia cespitosa*, *Hordeum brachyantherum*, and *Poa pratensis* had decreased, while the cover of *Carex utriculata*, *Scirpus microcarpus*, and *Carex simulata* had increased. Similar vegetation responses have been reported from southern Finland, where raising the water table of two drained fens increased *Eriophorum vaginatum* cover (Komulainen et al. 1999, Jauhiainen et al. 2002), and from northeastern Germany, where rewetting a fen allowed establishment of typical fen species, an increase in *Typha latifolia* and *Juncus effusus*, and a corresponding decrease in grassland species such as *Festuca arundinacea* (Richert et al. 2000).

In wetlands such as Drakesbad Meadow where parts of the meadow remained hydrologically intact during the twentieth century, post-restoration vegetation changes may occur fairly rapidly (Oomes et al. 1996, Jauhiainen et al. 2002) due to the presence of nearby seed sources and the ability of sedges and other species to spread by vegetative or clonal growth. In addition, the dissimilarity of the pre-restoration standing vegetation and the seedbank of impacted sites indicates the importance of soil seed banks for many wetlands species, including *Carex* (Thompson et al. 1997). In germination experiments with *Carex* species, van der Valk et al. (1999) found that the reestablishment of high soil moisture levels was critical to germination. Contribution of the seedbank to plant community development depends on how closely the reestablished hydrologic regime mirrors the germination requirements of individual species (Leck 1989, van der Valk et al. 1999). The short-term change in plant species cover in Drakesbad Meadow suggests that our restoration efforts were hydrologically and ecologically successful.

Conclusions

Onsite hydrologic modifications that occurred prior to acquisition of Drakesbad Meadow by the National Park Service continued to degrade the fen-wet meadow complex through the twentieth century. However, off-site impacts resulting from a National Park Service constructed road resulted in further degradation of the meadow. Indicators of past hydrologic conditions present within the oil seedbank, vegetation, and soil composition were essential to identify significant off-site impacts. The long term stability of the meadow complex, achieved through restoration and/or management, must include a thorough understanding of the site hydrologic regime because activities that alter groundwater and surface-water flowpaths may have unintended and unforeseen impacts on ecosystems, which depend upon the integrity of these flowpaths for their persistence.

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