WETLANDS, Vol. 18, No. 3, September 1998, pp. 335–345

HYDROLOGIC RESTORATION OF A FEN IN ROCKY MOUNTAIN NATIONAL PARK, COLORADO, USA

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Abstract: Big Meadows, a 63-ha fen in Rocky Mountain National Park (RMNP), was ditched for agricultural purposes in the early part of this century. Although use of the ditch ceased after the establishment of RMNP in 1915, it continued to intercept sheet flows in the central and southern portions of the fen, causing the ground-water level to decrease and aerobic soil conditions to develop in the mid- to late-summer of most years. In 1990, the ditch was blocked in an attempt to restore the hydrologic regime in the central and southern portions of the fen. Water-level data from three years prior to restoration and four years after restoration show that blocking the ditch successfully restored surface sheet flow, high late-summer water-table levels, and anaerobic soil conditions in much of the central and southern portions of the fen. Conditions in these areas are now similar to those in the northern portion of the fen. The long-term data from this site also indicate that summer rainfall has a greater influence on the magnitude of late-summer drying than the size of the winter snowpack. In a post-restoration year with extremely low rainfall in July and August, water levels throughout the fen decreased to levels similar to those observed throughout most of the pre-restoration period. The study suggests that this and other fens in the southern Rocky Mountains are extremely sensitive to summer precipitation and the hydrologic changes created by even small ditches or water diversions.

Key Words: fen, hydrology, restoration, Colorado, Rocky Mountains

INTRODUCTION

In many portions of the world, peatlands have been used for fuel or horticultural materials by direct harvesting, or they have been converted to agricultural or silvicultural uses by the construction of drainage ditches. These activities have been well-studied in Europe and Asia (UNESCO 1975, Zuidema 1975, Stewart and Lance 1983, Coulson et al. 1990, Göttlich et al. 1993, Heathwaite et al. 1993), Canada (Rubec et al. 1988, Dang and Lieffers 1989, Hillman 1992), and in a few areas of the U.S., such as Minnesota (Rutter 1955, Boelter 1972, Glazer et al. 1981, Glazer 1987, Garfi and Brooks 1990, Bradof 1992, Keirstead 1992). In contrast, there have been almost no detailed studies on the effects of ditches, water diversions, or mining in peatlands in the western United States or other mountainous regions.

Peatlands occur where soil saturation retards the decomposition of organic matter, allowing it to accumulate (Moore and Bellamy 1974, Sanger et al. 1996). In humid maritime and some high mountain regions, precipitation alone is sufficient to maintain saturated soils. However, in regions where potential evapotranspiration exceeds precipitation, additional surface or ground-water inflows, or both, are necessary to maintain saturated soils (Cooper 1990, Mitsch and Gosselink 1993, Cooper and Andrus 1994).

The southern Rocky Mountains region has a continental climate with warm, dry summers, and peatlands occur only in areas with consistently high water tables (Cooper 1990). These water tables are sustained by local hillslope drainage (Cooper and Andrus 1994) or local or regional ground-water discharge (Cooper 1996). The dependence of Rocky Mountain peatlands on ground-water discharge means that they are all fens and are often extremely sensitive to climate variability or changes in the supply of ground water due to water diversions (Heathwaite et al. 1993).

Big Meadows is a 63-ha fen in Rocky Mountain National Park that was ditched for agricultural use prior to the establishment of the Park in 1915 (Figure 1). Earlier studies determined that even though agricultural activities ceased when the Park was formed, the ditch was still lowering water tables in the central portion of the fen (Schuter 1988, Cooper 1990). On the

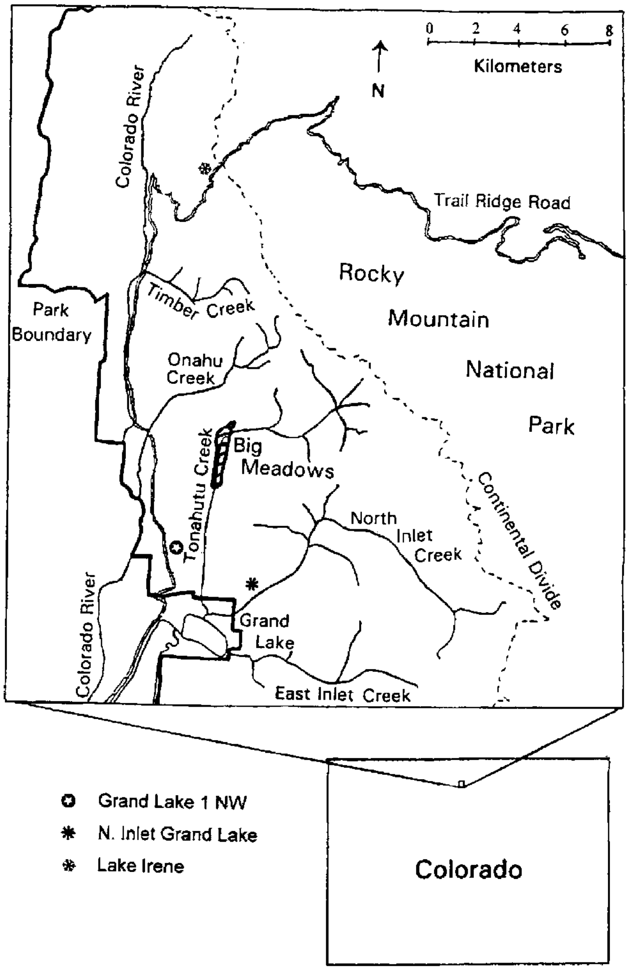

Figure 1. Location of the study area in Rocky Mountain National Park, Colorado.

basis of these investigations, a restoration program was designed and implemented in 1990.

Our hydrologic investigations have continued from 1987 to the present, and in this paper, we analyze three years of pre-restoration and four years of post-restoration water-level data to evaluate both the effects of the ditch and the success of the restoration project. These data provide an important case study of a restoration project in a high elevation peatland and insights into the hydrologic functioning of boreal-type fens near the southern limit of their occurrence in North America.

STUDY AREA

The Big Meadows wetland lies upstream of a glacial end moraine in the Tonahutu Creek drainage in the southwestern corner of Rocky Mountain National Park, Colorado at 2,865 m elevation (Figure 1). Tonahutu Creek drains westward from the Continental Divide and is a headwater tributary of the Colorado River. The northern and western area of Big Meadows is a fen supported by ground-water discharging from the toes of adjacent hillslopes, upward seepage from mineral soil, and seepage from spring-fed streams. In the fen portions of the wetland, up to 2 m of peat has accumulated on alluvial and glacial material. Adjacent to Tonahutu Creek, recent alluvial deposits occur at the surface, and no peat is present.

The fen is gently sloping, and its vegetation is dominated by the sedges *Carex aquatilis* Wahlenberg and *C. utriculata* Boott, with the willow *Salix planifolia* Pursh. being abundant on the fen margins where mineral-rich ground water discharges from hillside aquifers (Cooper 1990) (nomenclature follows Weber and Wittmann 1996). Conifer forests dominated by *Picea engelmannii* (Parry) Engelmann, *Pinus contorta* Douglas ssp. *latifolia* (Engelmann) Critchfield, and *Abies bifolia* A. Murray occur on adjacent hillsides. The chemistry of surface water in the fen is typical of that found in granitic watersheds in the Rocky Mountains, being circumneutral to moderately acid, with extremely low concentrations of mineral nutrients (Cooper 1990, Cooper and Andrus 1994).

Big Meadows is subject to a strongly seasonal, snowmelt-driven hydrologic regime. In May and June, snowmelt runoff floods the area with up to 10 cm of slowly flowing water. Since summer precipitation is less then potential evapotranspiration, water tables typically decrease during the summer and are deepest from late August through September. The water table begins to rise in late September or October when evapotranspiration decreases. The duration and timing of the summer water-table drawdown is critical, as high water tables are necessary to maintain anaerobic soil conditions and retard the decomposition of organic matter.

In the early 1900s, a ditch was constructed through the central and southern portions of Big Meadows to enhance hay production for livestock. This ditch drains water from the fen to Tonahutu Creek and is approximately 500 m in length, 0.5 m wide, and up to 1.0 m in depth (Figure 2). Although the ditch has not been maintained since 1915, it continues to capture surface water and erode deeper into the peat. Topographic and botanical evidence indicates that, in the absence of the ditch, surface water would flow south through Big Meadows as a water track or path of concentrated water flow (Wright et al. 1992). This water track still exists in the northernmost portion of Big Meadows. We used water levels in this northern area (the area around wells 46 to 60 in Figure 2) as controls to evaluate the effects of climatic differences between the pre- and post-restoration study periods.

The diversion of this surface water, combined with

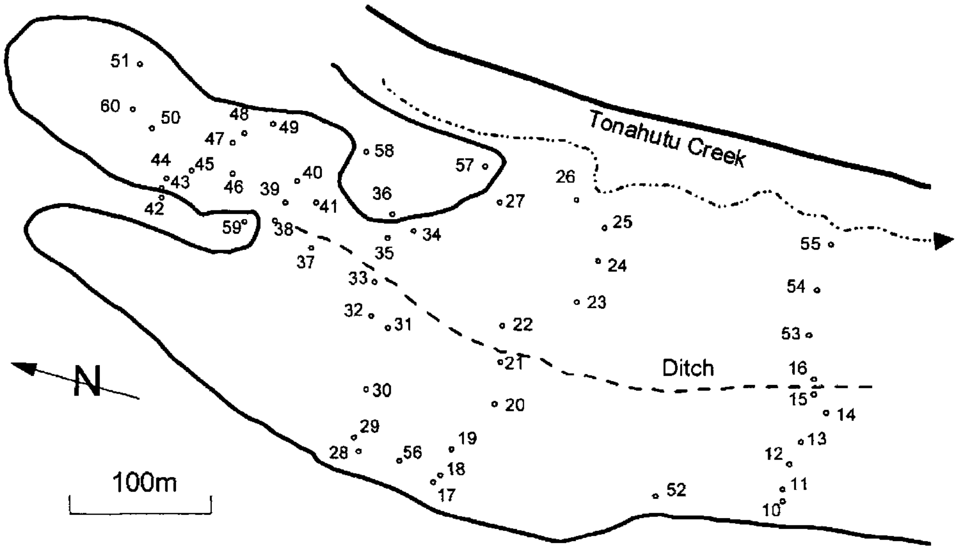

Figure 2. Location of the ditch in the Big Meadows study area. Also shown are the location of study wells and Tonahutu Creek. Areas outside the dark line and near wells 58 and 59 are forested.

the lowering of the water table by the incised ditch, caused ground-water levels in the central portion of Big Meadows to drop to more than 40 cm below the soil surface from mid-July through the fall of most years prior to the restoration. The low water table allowed soils to dry and oxidizing conditions to develop. The concern was that oxidizing conditions would increase decomposition rates and result in a long-term loss of peat and substantial ecological changes in the fen.

Since Big Meadows is located 3.5 km from the nearest road, filling the ditch with imported soil was not practical. Instead, 44 pieces of 150-cm-long, 90-cm-wide, and 3-mm-thick galvanized sheet metal were installed across the ditch to block the flow of water in 1990.

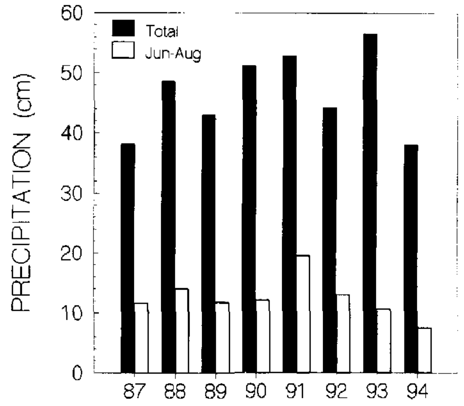

Figure 3. Total water year and June through August precipitation, 1987–1994, recorded at U.S. Weather Service station Grand Lake 1NW. Mean annual precipitation is 51.5 cm, and mean June–August precipitation is 15.0 cm.

METHODS

Hydrology and Climate

Fifty ground-water monitoring wells were installed in Big Meadows (wells 10–60 in Figure 2) in June, 1987. All wells were installed by hand to a depth of 2–2.5 m, and each well was cased with 5-cm-diameter PVC pipe slotted in the entire section below the ground surface. Wells were back-filled with native soil and a cap of native clayey soils. Wells were developed

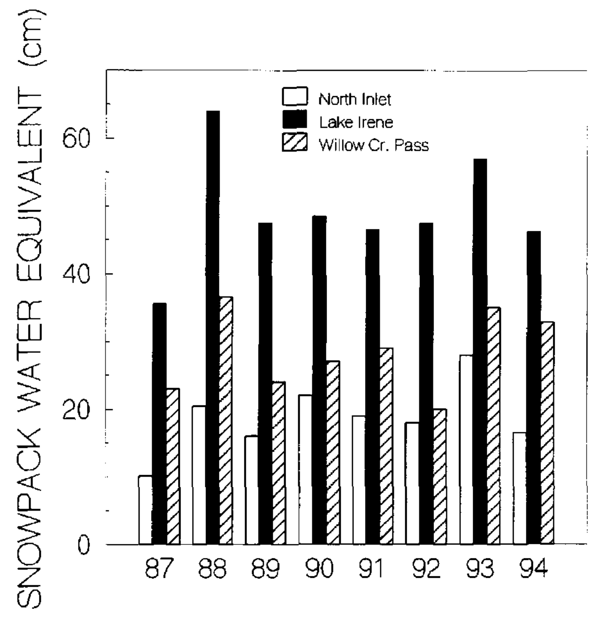

Figure 4. Total snowpack water equivalent for 1 May 1987–1994 for North Inlet, Lake Irene, and Willow Creek Pass stations in Rocky Mountain National Park.

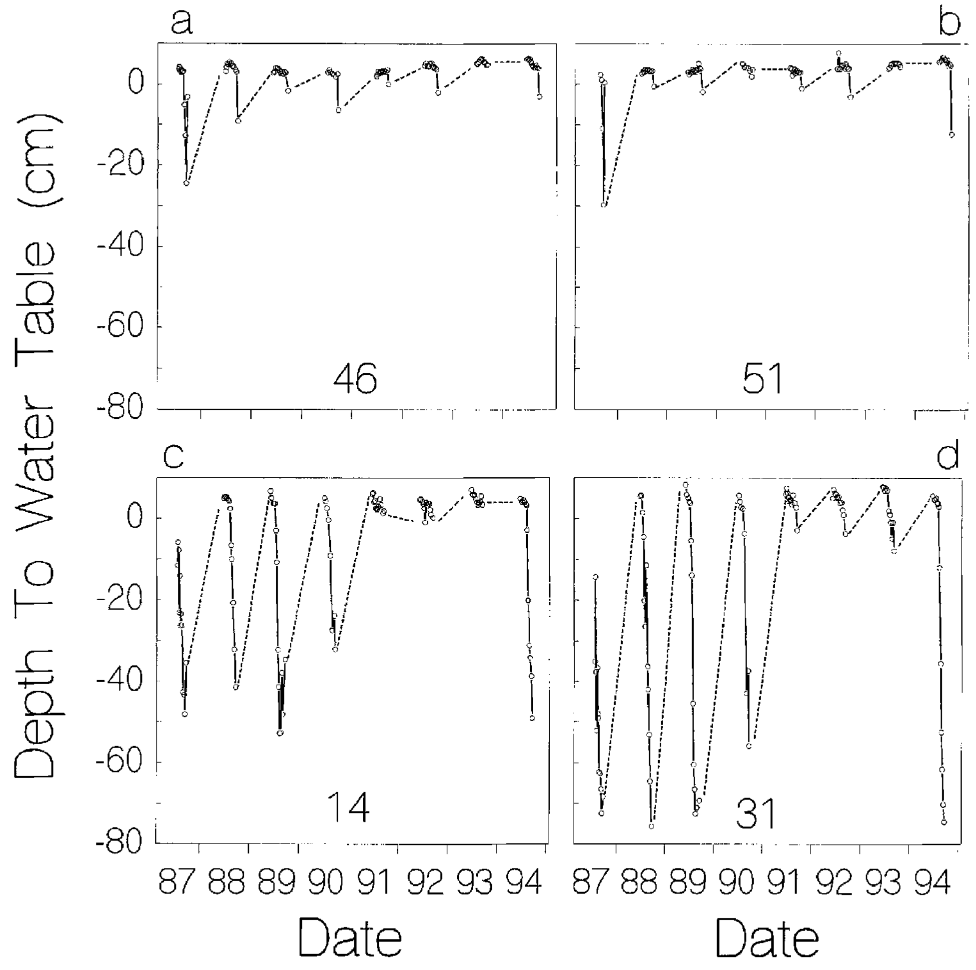

Figure 5. Depth to water table during 1987–1994. Monitoring wells 46 and 51 represent the undisturbed water track, and wells 14 and 31 represent the ditched water track, in Big Meadows. Circles are data points connected by solid lines. Dotted line approximates winter water-table recovery.

by pumping three casing volumes of water. All wells were monitored approximately weekly from the time Big Meadows became snowfree in early summer through August and less frequently during the fall. Here, we analyze well data from 1 June to 31 August for each year from 1987 through 1989 and 1991 through 1994. Water-level data from 1990 are not analyzed here because they represent the year when the ditch restoration was taking place and therefore don't represent either pre- or post-restoration conditions.

Precipitation and snowpack records were used to determine which pairs of years prior to and following restoration could provide the most valid comparisons. The nearest daily precipitation data were from the U.S. Weather Service station at Grand Lake 1NW (Figure 1), located five km southwest of Big Meadows at 2,700 m elevation. Records at this station date back to 1950. Snowpack water equivalent (SWE) data were available from three stations in the upper Colorado River basin within Rocky Mountain National Park: (1) Lake Irene, located 10 km north of Big Meadows at 3,260 m elevation; (2) Willow Creek Pass, located 15 km west of Big Meadows at 2,907 m elevation; and (3) North Inlet, located 5 km south and slightly east of Big Meadows at 2,740 m elevation (Figure 1). The most comparable pairs of years were 1988/1993, and 1989/1992. These pairs have similar spring SWE values as well as similar amounts and timing of summer precipitation.

Oxidation-reduction potential was measured weekly during June–August 1988–1989 at ten sites in the study area using bright platinum electrodes constructed by welding platinum wire onto copper as described by Faulkner et al. (1989). A total of nine electrodes were installed at each site, with three replicates at 7, 15, and 30 cm depths. Redox values are reported as field measurements corrected for the Calomel reference electrode (DeLaune et al. 1983, Faulkner et al. 1989, Mitsch and Gosselink 1993), not SHE units. Redox potentials greater than +350 mv are considered to indicate oxidizing conditions, while lower values indicate reducing conditions (Sikora and Keeney 1983).

Data Analyses

Depth to water table data for study years were analyzed using agglomerative cluster analysis to determine which wells had the most similar hydrographs for each year. Cluster analysis is an explicit way of identifying groups in raw data and is used to classify sites (Jongman et al. 1995). We used the depth to water table on each sample date for each well as the input data to classify wells relative to other wells for each year. The cluster analysis was calculated using Euclidean distance and unweighted pair grouping methods (UPGMA) with the computer program Multivariate Statistical Package 2.1 (Kovach 1993). Dendrograms between paired pre- and post-restoration years were compared to determine which wells shifted position following restoration.

For all study years other than 1990, we determined the number of days between 1 June and 31 August that the water table in each well was above the ground surface and at depths of 0–20 cm, 20–40 cm, and greater than 40 cm, respectively. Field observations of sedge roots indicate that these four categories represent standing water, the upper part of the rooting zone, the lower part of the root zone, and below the root zone, respectively. Tables were made for each year for each depth class using (1) all wells, (2) wells in the ditched portion of the water track, and (3) control wells. The proportion of days between 1 June and 31 August that all wells, water-track wells, and control wells had a water table within each of the four categories described above was compared in pairwise fashion between years using Z-tests (Zar 1984). These analyses were used to indicate whether the restoration project resulted in higher water tables during the summer and the significance of year-to-year differences in precipitation before and after restoration.

RESULTS

Precipitation During the Study Period

Mean annual precipitation for Grand Lake 1NW is 51.5 cm, with a standard deviation of 9.8 cm. Annual precipitation has ranged from 36.8 cm in 1966 to 88.9 cm in 1984. Mean summer (1 June through 31 August) precipitation is 15.0 cm, with a standard deviation of 5.7 cm. Total summer precipitation has varied from 4.4 cm in 1978 to a high of 38.4 cm in 1984. Mean precipitation during June, July, and August is 4.2, 5.3, and 5.5 cm, respectively, with standard deviations of 3.0, 2.5, and 2.8 cm, respectively. These values indicate that summer precipitation is considerably more variable than annual precipitation, and there is more variability for individual months than for the summer as a whole.

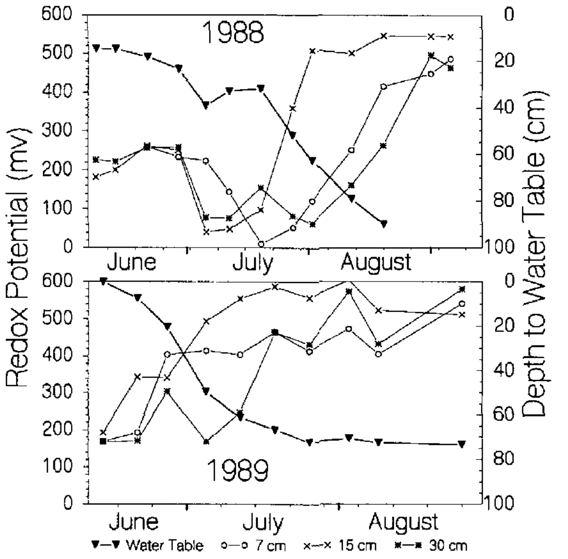

Figure 6. Redox potential at 7, 15, and 30 cm soil depths (mean of n = 3 at each depth), and depth to the groundwater table during June–August 1988 and 1989 near well 31.

The years 1987 and 1994 were two of the four driest on record, with total annual precipitation of 37.6 and 38.0 cm, respectively (Figure 3). The highest total precipitation (57.0 cm) for the study period was in 1993, but in contrast to 1987 and 1994, this was within one standard deviation of the 45-year mean. The lowest July precipitation total on record (0.9 cm) occurred in 1994, and 1991 had the 5th highest (8.6 cm). Since 1991 and 1994 were both post-restoration years, these differences allowed us to evaluate the effects of high and low mid-summer precipitation on water tables in the control and the restoration areas.

The 1 May SWE values for 1987–1994 indicate that all three stations (North Inlet, Lake Irene, and Willow Creek Pass) are correlated ($r>0.77$, $p<0.05$). Lake Irene, the highest elevation site, consistently has much more SWE than North Inlet, the lowest elevation site (Figure 4). Since most of the annual precipitation accumulates in the seasonal snowpack, late April SWE at these three stations is correlated ($p<0.05$) with total annual precipitation at station Grand Lake 1NW. SWE measurements during the 1988 and 1989 water years indicated that Big Meadows had a higher SWE than Willow Creek Pass but less than Lake Irene.

Hydrologic Analysis

The hydrographs for wells 46 and 51 illustrate the undisturbed hydrologic regime of the water track in

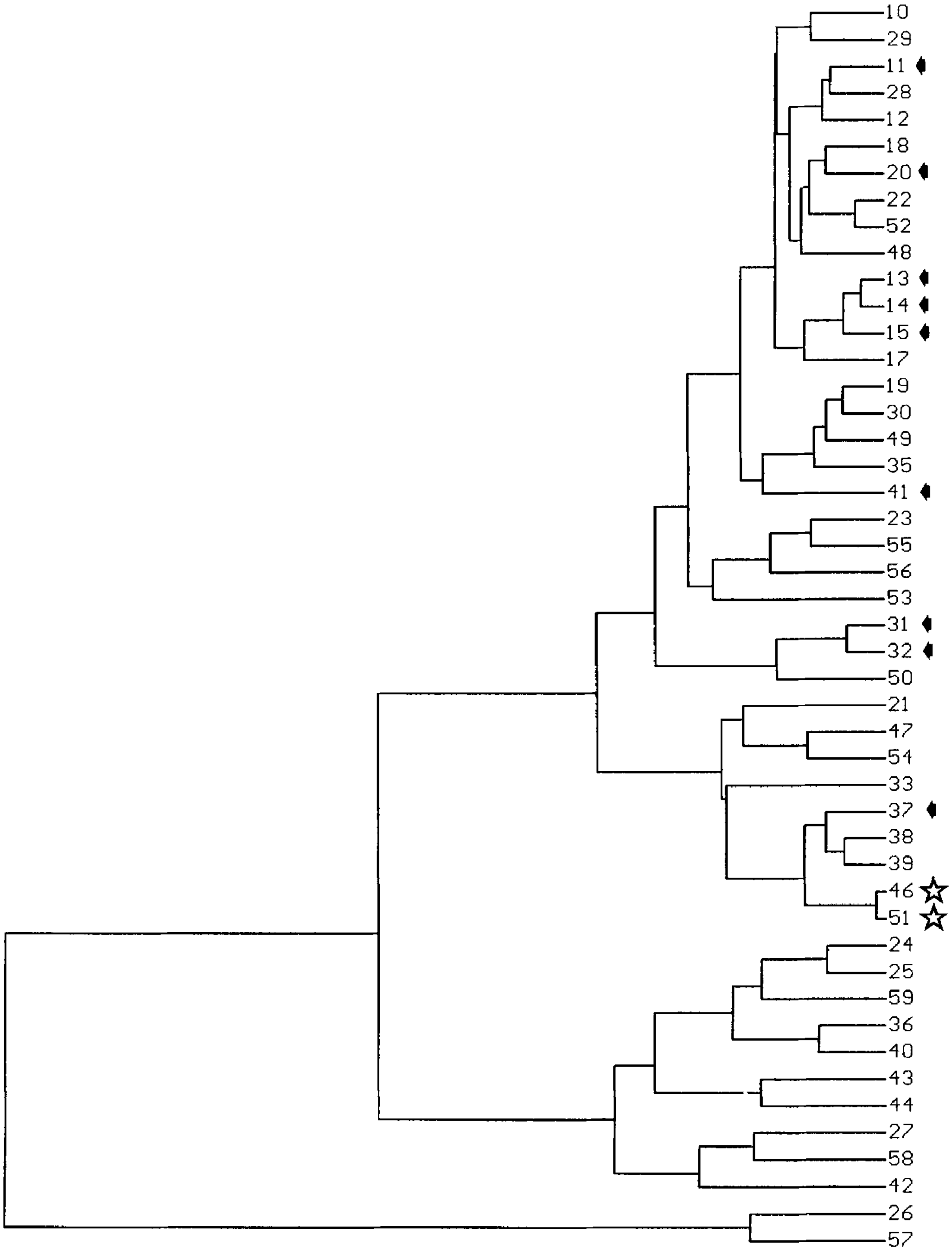

Figure 7. (a) Dendrogram for cluster analysis of well data for 1989. Wells marked with arrows occur in the ditched water track and do not cluster near control wells 46 and 51 in the undisturbed water track (marked with stars). Maximum Euclidean distance is 457. (b) Dendrogram for cluster analysis of well data for 1992. Formerly ditched water-track wells cluster together with control wells 46 and 51. Also clustering with these water-track wells are mire-margin wells 10, 48, 18, and 28 and well 54 located at a spring. These sites also have water tables near the soil surface for the entire summer in all but the driest years. Maximum Euclidian distance is 502.

the control area of Big Meadows (Figures 5a and 5b). Sheet flow occurred for most of the summer at these two sites during all eight study years. Only in 1987 and 1994 did the water table drop more than 10 cm below the soil surface for a short period of time in late August. Redox potential measurements at well 46 during 1987–1989 indicate that the soils did not become aerobic (Cooper 1990).

In the ditched water track portion of Big Meadows, the water table in wells 31 and 14 (Figures 5c and 5d)

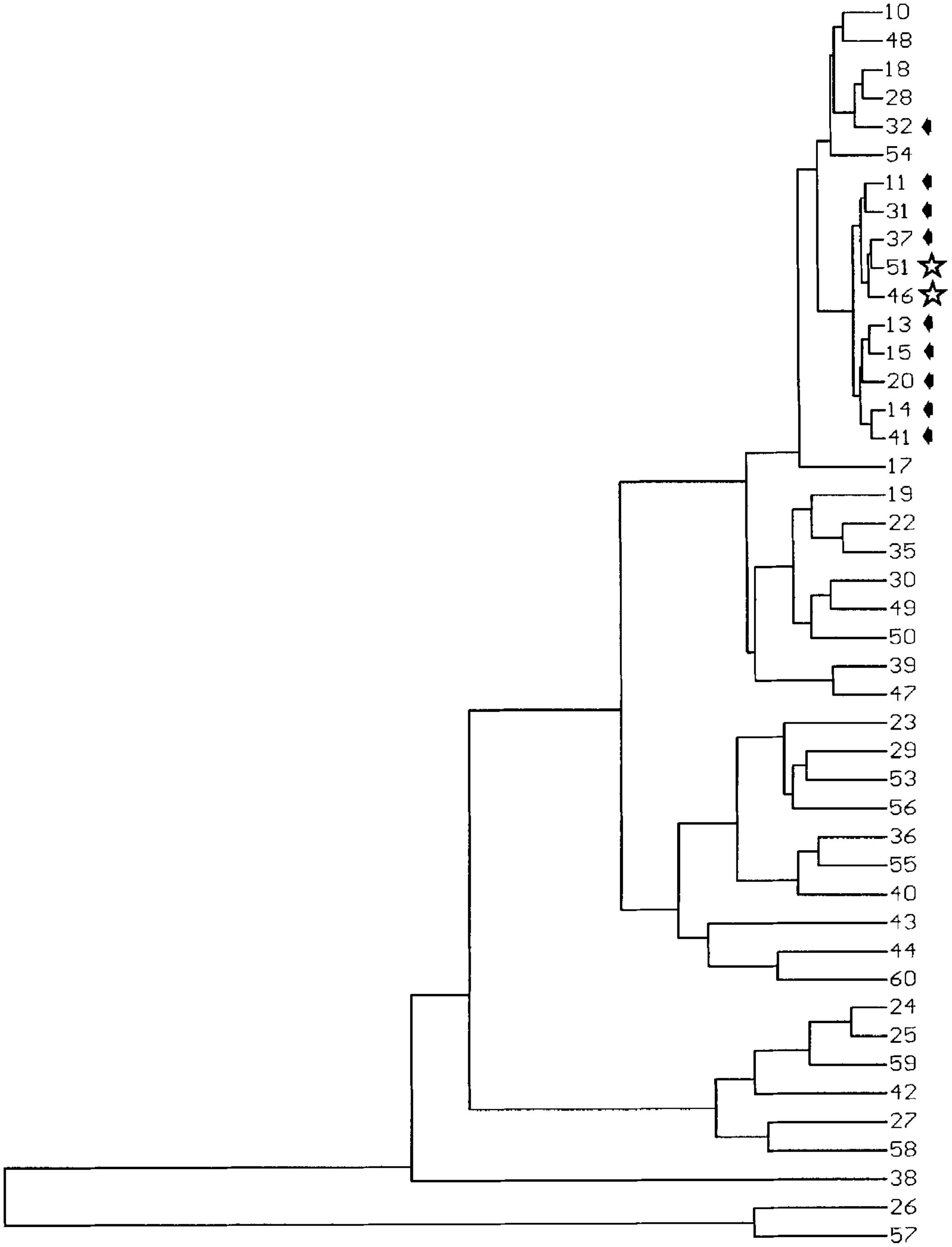

Figure 7. Continued.

dropped to 40–70 cm below the soil surface in July and August in all three pre-restoration years (1987–1989). In contrast, the water table remained near the soil surface for the entire summer during the first three post-restoration years (1991–1993) and was very similar to the water levels in wells 46 and 51. In 1994, the below-normal summer precipitation caused the water table in wells 31 and 14 to drop to levels similar to those observed prior to restoration.

Redox potential measurements taken near well 31 in the ditched portion of the water track during 1988 and 1989 indicated that wetland soils throughout the study area are anaerobic in early June. As the water table dropped, upper soil horizons became aerobic first, while aerobic conditions developed at 30 cm depth 1–2 weeks later (Figure 6). In 1987 and 1988, soils began to oxidize when the water table dropped to more than 20–40 cm below the soil surface. The upper 15 cm of soil became aerobic in late June during the dry year 1989, while during the wet year 1988,

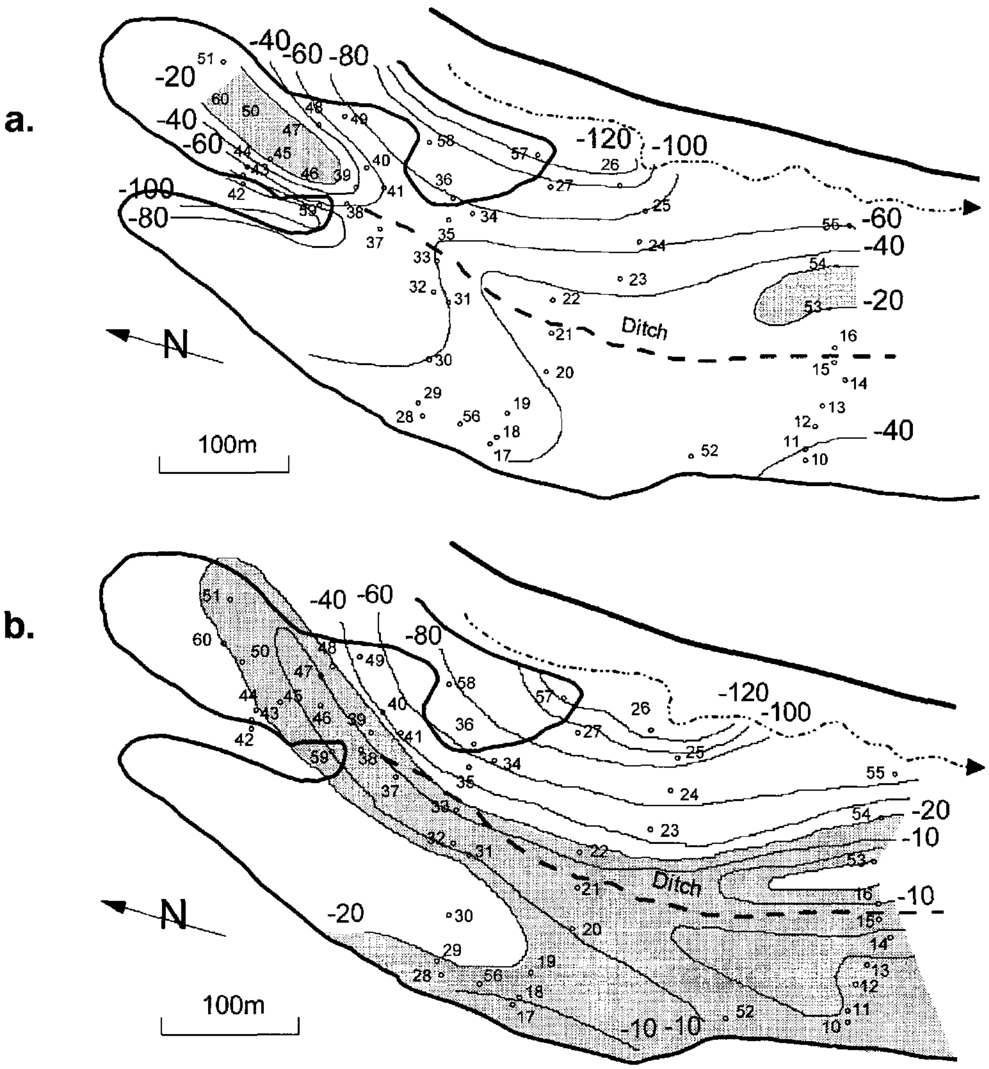

Figure 8. (a) Map showing depth to the ground-water table for 1 August 1989. Shaded areas have a water table within 20 cm of the soil surface. (b) Map showing depth to the ground-water table for 1 August 1992. Shaded areas have a water table within 20 cm of the soil surface and indicate the position of the restored water track.

aerobic conditions did not develop until nearly a month later (Figure 6). Sites such as well 46, where the water table rarely drops below 20–30 cm depth, remained anaerobic all summer.

The cluster analysis of well hydrographs for 1989 shows that the wells in the ditched portion of the fen (wells 11, 13, 14, 15, 20, 31, 32, 37, and 41, identified with arrows), are in different portions of the dendrogram from the wells in the control area upstream of the restoration project (wells 46 and 51, marked with stars) (Figure 7a). However, in the 1992 dendrogram, these same wells were clustered with wells 46 and 51, indicating that their annual hydrographs were very similar (Figure 7b). A similar shift in well positions was observed in a comparison of the 1988 and 1993 dendrograms. Also clustering with the control wells and restored water track wells in the 1992 hydrograph are peatland margin wells 10, 48, 18, and 17 and one spring site, well 54, all of which have water tables near the soil surface for most of the summer (Figure 7b).

A map of the water table depth below the soil surface in mid-August 1989 shows that the water track in the upstream portion of Big Meadows is truncated by the ditch (Figure 8a). Water tables in the central part of Big Meadows are generally 40–80 cm below the soil surface and would have aerobic soils. In contrast, the depth to water table map for August 1992 (Figure 8b) shows the water table within 20 cm of the soil surface extending through all of Big Meadows except for the portion adjacent to Tonahutu Creek, and anaerobic soils would occur through this entire area.

Pairwise comparisons between years indicate that water tables in the control wells were at or above the ground surface for a significantly shorter period of

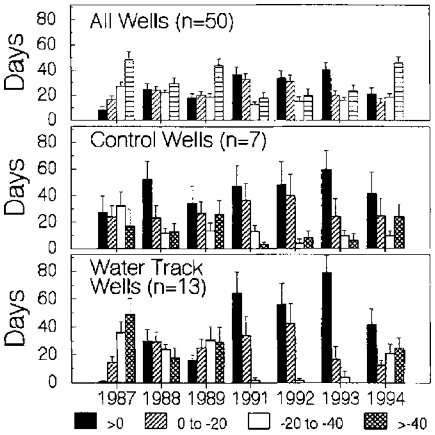

Figure 9. Mean (+1 se.) number of days that all wells, control wells, and wells within the area of the restored water track had a depth to water table above the soil surface (>0), between the soil surface and 20 cm depth, between 20 cm and 40 cm depth, and greater than 40 cm depth for all study years.

time in 1987 and 1989 than 1988 (Z-tests, $p<0.05$), 1991, 1992, and 1993 ($p<0.01$), but not than 1994 ($p>0.05$). There was no significant difference in the duration of surface inundation between 1988 and 1993 or between 1989 and 1992, indicating that the comparison of these years using cluster analysis and depth to water table is valid.

When all wells, including the control area and water track, were analyzed together, 1987 and 1989 were the years with the shortest duration of surface inundation and the shortest duration of a water table within 20 cm of the ground surface (Figure 9). There was no significant difference (Z-tests, $p>0.05$) in the proportion of days with surface inundation between 1987, 1989, and 1994, yet significant differences did occur between these three years and 1988, 1991, 1992, and 1993 ($p<0.01$).

For wells in the formerly ditched portion of the water track (water-track wells in Figure 9), there was no statistically significant difference in the duration of surface inundation between 1987 and 1989, but these two years were significantly drier than all other years. The wettest pre-restoration year, 1988, was not significantly different than 1994, but 1988 was significantly different than the wetter post-restoration years (1991, 1992, and 1993). Thus, water levels in the ditched water-track area in 1988, a pre-restoration year with above average precipitation, were comparable to the water-table levels observed in 1994, a post-restoration year with below average precipitation.

The comparison of post-restoration water levels between years with average (1992), high (1993), and low (1994) total precipitation illustrates that during average-to-wet years, the water table in the restored water-track remains near the soil surface for nearly the entire summer, while in a dry year, such as 1994, the water table dropped to well below the soil surface (Figure 9). Thus, differences in the amount of summer precipitation can result in important differences in wetland ground-water levels. For example, greater than average mid-summer rain in 1991 caused water tables to rise, while in 1994, when little summer rain fell, the water table dropped sharply (Figure 5c) even though winter snowpack was relatively similar between these two years (Figure 4).

DISCUSSION

Since the early 1900s, the ditch in Big Meadows has successfully diverted the water track to Tonahutu Creek and thereby removed a major source of water from much of the fen. Analysis of well and redox potential data indicate that prior to 1990, the water table in much of the study area dropped sufficiently far below the soil surface to create aerobic conditions in the upper part of the soil for at least half of the summer in all but high summer-precipitation years.

After blocking the ditch, the water table through the central portion of Big Meadows remained near the soil surface for the entire summer during 1991, 1992, and 1993. Although soil redox potential data are not available during this period, the relationship observed between redox potential and ground-water levels in 1987–1989 indicates that anaerobic conditions would have been maintained for the entire summer. Since water tables were below 20 cm for an average of only about a week from 1991 through 1993 in the restored water track area as compared to nearly seven weeks before restoration, the rate of organic matter decomposition has been greatly reduced, and the fen most likely is accumulating organic matter in all but the driest years.

Between 20 June and 1 August 1994, only 1.1 cm of rain fell in the study area. The lack of precipitation and correspondingly high evapotranspiration caused the water table in the restored water track area to drop to levels similar to the pre-restoration year 1988. This similarity indicates that prior to restoration, soils within the ditched portion of the water track became aerobic even during a relatively high precipitation year such as 1988. We believe that the ditch effectively maintained Big Meadows in a state of severe and prolonged drought for much of the 20th century. The reduction in soil saturation allowed *Deschampsia cespitosa* (L.) P. Beauvois (tufted hairgrass), a native grass common in seasonally dry mineral soils, to invade the fen. This species has the third highest canopy cover and third highest constancy of any species in the *Carex aquatilis-Psychrophila leptosepala* (de Candolle) Weber community type, which occupies the central portion of the fen (Cooper 1990).

^{14}C dates from the base of the peat body indicate that the Big Meadows fen originated after the retreat of Pinedale glaciers nearly 12,000 years BP (Cooper 1990). Although there may have been alternating cycles of peat accumulation and decomposition during the Holocene, spring snowmelt and summer precipitation have been sufficiently consistent to allow the accumulation of 2 m of peat in much of Big Meadows. The construction of the ditch and resultant annual drying of the central fen area may have been one of the most significant environmental changes since the origin of the fen, although it does not appear that subsidence of the peat surface occurred.

Blocking the ditch has, at least temporarily, reduced the effectiveness of the ditch for diverting surface waters and caused the water track to again flow the entire length of Big Meadows. However, some surface water still flows in the ditch, and this has eroded the soil around some of the metal sheets. Once initiated, this erosion is likely to proceed and threaten the effectiveness of the initial restoration effort. The only permanent remedy is to fill the ditch with soil and revegetate the area with the rhizomatous sedges that dominate the fen.

The data collected in this study shows that fens in the southern and central Rocky Mountains are extremely sensitive to the hydrologic changes that even small ditches or other water diversions can create. Once a ditch is created, it is self-perpetuating, and an active restoration effort must be undertaken to remove the ditch or eliminate the drainage of water by the ditch. Fens in this region do not appear to be sustainable under the drought conditions produced by ditches, water diversions, or ground-water pumping, all of which would lower water tables. We expect that many fens may also be extremely sensitive to even small changes in the amount or timing of summer precipitation. Much of the peat accumulated during the Holocene may have occurred during climate periods when mid- to late-summer precipitation totals were consistently high.

ACKNOWLEDGMENTS

Data collection was funded by the National Park Service's Water Resources Division, Rocky Mountain National Park, the U.S. Fish and Wildlife Service, and EPA Region VIII. We thank Dr. Ken Czarnowski, Joel Wagner, Dr. Richard Kiegley, and David Stevens of the National Park Service, Dr. Charles Segelquist and Lee Ischinger of the U.S. Fish and Wildlife Service, and Dr. Gene Reetz of EPA Region VIII for their assistance and cooperation. We give special thanks to Jeff Connor, Rocky Mountain National Park, for implementing the restoration project. Field assistance was provided by Kelli Schuter, Brick Smith, Kevin McBride, Thomas Cottrell, David Gilbert, Sally White, Patricia Yamaguchi, Martha Aitken, and Rodney Chimner. We thank Drs. Ken Wilson and Ken Burnham for statistical advice and Larry Martin, Joel Wagner, Dr. Donald Siegel, and an anonymous reviewer for comments on early drafts of this work.

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Manuscript received 14 April 1997; revision received 13 April 1998; accepted 24 April 1998.