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HYDROLOGIC INTERACTIONS BETWEEN AN ALLUVIAL FAN AND A SLOPE WETLAND IN THE CENTRAL ROCKY MOUNTAINS, USA

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Abstract: Slope wetlands generally occur at breaks in slope where discharging ground water maintains moist soil conditions. They often are found on the perimeter of highly permeable alluvial fans, but there have been no detailed hydrologic studies of these particular wetlands. We combined stream and spring flow measurements with five years of water-level and piezometric data to understand the hydrology of a 1.6 ha slope wetland at the base of a 5.2 ha alluvial fan in the central Rocky Mountains of Colorado. Step changes in streamflow inputs resulting from an upstream water diversion helped confirm the linkages inferred from the hydrometric data. Nearly 30% of the streamflow along a 180-m reach on the alluvial fan was lost to seepage. Discharge from two springs at the toe of the alluvial fan was eliminated and the piezometric head in the toe of the fan decreased by more than 80 cm within 1–2 days after the stream was diverted, indicating that stream seepage is the primary source of ground-water recharge for the alluvial fan. Streamflow and ground water discharging at the base of the alluvial fan were the primary wetland inflows, with summer precipitation playing a relatively minor role. Consequently, wetland water levels declined by up to 75 cm after the diversion began operating. The largest declines were in the lower part of the wetland, where surface sheet flow from the stream was the main water source. Continuing ground-water discharge into the upper part of the wetland limited the water level declines to less than 40 cm. The importance of streamflow as a water source distinguishes slope wetlands adjacent to alluvial fans from those found in other settings and makes them particularly vulnerable to upstream water diversions.

Key Words: slope wetland, hydrology, alluvial fan, stream-ground-water interactions, water diversion, Rocky Mountains

INTRODUCTION

Slope wetlands are a distinct class of wetlands that occurs on or at the foot of hillslopes (Novitzki 1979, 1982, Brinson 1993, Cole et al. 1997, Shaffer et al. 1999). Although limited in spatial extent, they provide several important hydrologic, biogeochemical, and biological functions (Stein et al. 2004). The hydrologic functions include the interception of surface water and ground water, and modification of the delivery rate of this water to downslope environments. Biogeochemical functions, such as organic matter accumulation and export, are determined in large part by the hydrologic regime, as are biological functions such as the maintenance of characteristic and occasionally rare plant communities. Understanding the hydrology of slope wetlands is therefore essential to maintaining their ecological structure and function.

Landscape setting and wetland-upland interactions are important controls on wetland hydrology (Siegel 1988, Roulet 1990, Waddington et al. 1993, Devito et al. 1996, Branfireun and Roulet 1998, Fahey et al. 1998, Drexler et al. 1999, Fitzgerald et al. 2003). This is especially true for slope wetlands, which depend on water inflows from the adjacent upland (Windell et al. 1986, Brinson 1993, Cole et al. 1997, Johnson 2001). Most slope wetlands are supported primarily by ground-water inflows (Brinson 1993, Cole et al. 1997, Shaffer et al. 1999). The abrupt change in gradient at the base of the slope creates an upward component of flow, resulting in ground-water discharge into the wetland (Winter 1999).

Wetlands connected to regional-scale aquifers have relatively constant ground-water inflows, so water levels remain more stable during periods of reduced precipitation (Tóth 1963, Devito et al. 1996). In contrast, wetlands supported by localized aquifers typically

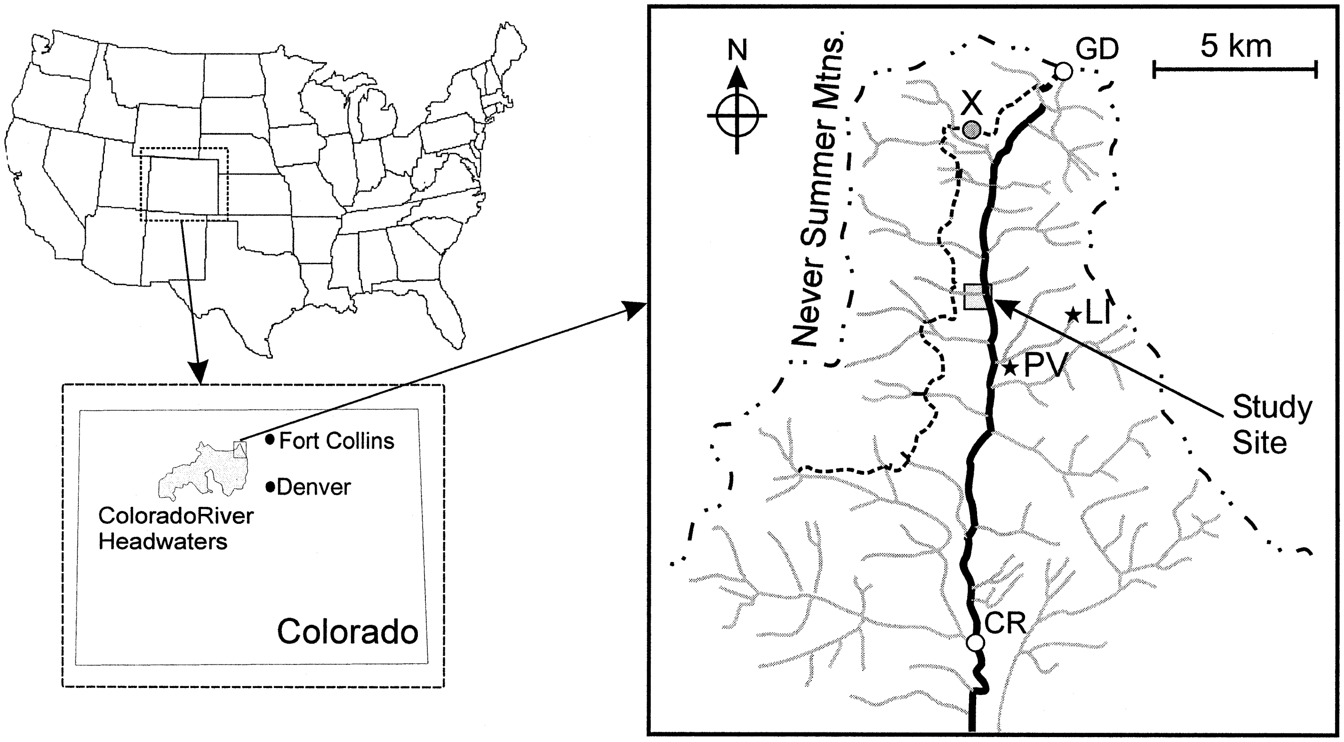

Figure 1. Map of the Colorado River headwaters near Grand Lake, Colorado. The thick solid line is the main stem of the Colorado River, and the thinner gray lines are tributary streams. The dot-dot-dash line indicates the Continental Divide, and the dashed line is the Grand Ditch. PV and LI are the Phantom Valley and Lake Irene SNOTEL sites, CR is the USGS gauging station on the Colorado River at Baker Gulch, GD is the Colorado Department of Water Resources gauging station on the Grand Ditch at La Poudre Pass, and X is the approximate location of the breach in the Grand Ditch in late spring 2003.

have more variable inflows, and wetland water levels have correspondingly greater amplitude and frequency of fluctuations. This is particularly true when aquifer recharge is derived from seasonal precipitation, snowmelt, or stream seepage, as there is greater potential for depletion of the aquifer storage during dry periods.

Slope wetlands can occur in conjunction with alluvial fans, where they may be supported by both local-scale ground-water inflows and by surface-water inflows from the fan (Siegel 1988). Alluvial fans are important geomorphic features in many landscapes but are especially common in montane areas where an abrupt decrease in stream gradient at a mountain front or valley margin causes alluvial sediment deposition. The alluvial fan sediments commonly comprise a localized unconfined aquifer that is at least partly recharged from stream seepage on the fan surface (Shimada et al. 1993, Herron and Wilson 2001, Houston 2002). Ground-water discharge from an alluvial fan into an adjacent slope wetland may therefore vary with streamflow. The importance of streamflow as both a direct water source and a source of ground-water recharge should distinguish slope wetlands adjacent to alluvial fans from those found in other settings. Furthermore, it suggests that these wetlands may be especially sensitive to human-induced streamflow modifications, such as those due to water diversions. However, there is little information on the hydrology of slope wetlands adjacent to alluvial fans or their sensitivity to human-induced changes in streamflow.

In this paper, we present a hydrologic study of a slope wetland adjacent to an alluvial fan in the central Rocky Mountains of Colorado, USA. We combined stream and spring flow measurements with five years of water-level and piezometric data to understand 1) the stream—ground-water interactions within the alluvial fan, 2) the hydrologic interactions between the alluvial fan and the wetland, and 3) the controls on wetland water levels. Step changes in streamflow caused by an upstream water diversion helped confirm the linkages inferred from the hydrometric data and provided greater insight than could have been obtained from a purely observational study.

STUDY SITE

The study focused on a 5.2-ha alluvial fan and an adjacent 1.6-ha slope wetland in the subalpine upper headwaters of the Colorado River in Rocky Mountain National Park in northern Colorado (Figure 1). The

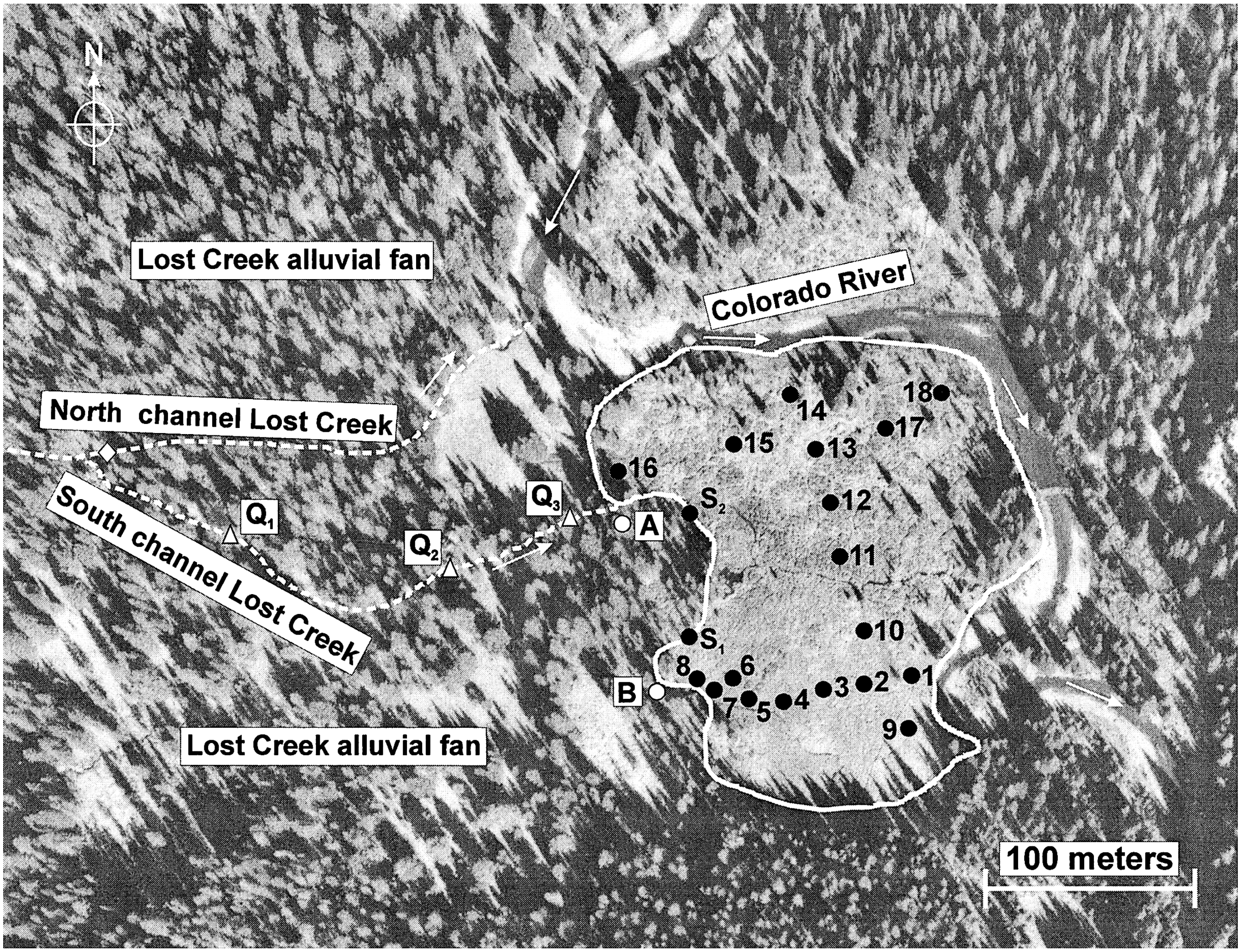

Figure 2. Aerial photograph of the Lost Creek study site depicting the stream-gauging stations Q_1, Q_2, and Q_3 (triangles), springs S_1 and S_2, monitoring wells and piezometer nests 1 to 18 (black circles), piezometers A and B (white circles), and the dam constructed in 1998 to divert water into the south channel in 1998 (diamond). The solid white line is the wetland boundary, and the dashed lines indicate the north and south channels of Lost Creek. Arrows indicate the direction of streamflow in Lost Creek and the Colorado River. The beaver dam in the Colorado River east of the wetland was not present during the study.

alluvial fan has a vertical relief of 70 m, an overall slope of 27%, and is located where Lost Creek, a headwater tributary of the Colorado River, reaches the main valley floor. Lost Creek splits into two channels at the apex of the alluvial fan (Figure 2). The north channel flows directly to the Colorado River, while the south channel discharges into the slope wetland. The wetland, which lies approximately 2 m above the baseflow stage of the Colorado River, consists of a series of gently inclined terraces formed by the accumulation of sand, silt, and peat in abandoned beaver ponds. Ground-water discharge from the toe of the fan flows into the upper portion of the wetland via two springs and diffuse seepage. Water from the south channel and ground-water seepage flow across the wetland as sheet flow and via a series of small channels before discharging to the Colorado River.

The flow of Lost Creek is affected by an upstream diversion, the Grand Ditch (Figure 1). Throughout most of each summer, this 24-km diversion intercepts all of the streamflow from the upstream drainage area of Lost Creek and twelve other headwater tributaries of the Colorado River. The ditch is unlined, so it intercepts a portion of the shallow ground-water flow, and it loses water to seepage on the downslope side. Field observations indicate that this seepage represents only a small fraction of the diverted water.

Water captured by the Ditch flows north to a low point on the Continental Divide and then into the east-flowing Cache la Poudre River. In the case of Lost

Table 1. Period of data collection, number of days with measurements, and dates of beginning and end of Grand Ditch flow diversions in 1996, 1997, 1998, 2002, and 2003.

	Measurement Dates		Measurement Days	Grand Ditch Diversion	
Year	First	Last		Start	End
1996	27 June	22 September	13	<27 June	>1 October
1997	11 June	30 September	22	27 June	22 September
1998	10 June	10 September	15	26 June	>10 September
2002	14 June	25 September	15	<14 June	Head gate not reopened until Ditch breach in 2003
2003	15 June	27 September	15	24 July	>1 October

Creek, 90% of the drainage area is above the Ditch. This means that when the Grand Ditch is operating, the only streamflow reaching the apex of the Lost Creek alluvial fan is derived from the 10% of the drainage area that lies below the Grand Ditch. Consequently, the flow of Lost Creek across the alluvial fan responds almost immediately to the beginning and the end of the diversion. We theorized that due to the small size of the Lost Creek alluvial fan and the correspondingly short flowpaths, the interaction between surface water and ground water could be determined by observing the ground-water response to diversion-induced streamflow fluctuations. Similarly, the hydrologic connection between the alluvial fan and the wetland could be determined from the wetland water-level response to changes in streamflow on the alluvial fan caused by the diversion.

The study area has a snowmelt-dominated, continental climate. Both the amount of precipitation and the proportion of snowfall increase with elevation. Mean annual precipitation at the Phantom Valley (PV) SNOTEL station (Figure 1), which lies approximately 2 km from the Lost Creek wetland and at a similar elevation (2750 m), is 640 mm with 42% falling as snow. Mean annual precipitation at the Lake Irene (LI) SNOTEL station, which is at an elevation similar to the Grand Ditch (3260 m), is 885 mm with 84% falling as snow. Precipitation at both SNOTEL sites is distributed evenly throughout the year, but from November through April, most of the precipitation accumulates as snow. Snowmelt typically occurs in early May at PV and in mid-June at LI. Mean total precipitation at PV for the summer months of May through September is 236 mm, with periodic thunderstorms occurring from late July until the end of August. Mean monthly temperatures at PV range from −9.6 °C in December to 12.4 °C in July. Mean monthly potential evapotranspiration (PET), calculated using the Thornthwaite method (Dunne and Leopold 1978), ranges from 0 in the winter months to 77 mm in July and exceeds the mean monthly precipitation by 10–20 mm in June, July, August, and September. Due to the late snowmelt and cold temperatures, the growing season only extends from late May through the end of August.

METHODS

Hydrometric data were collected approximately weekly during the snow-free period of mid-June through mid-September in 1996, 1997, 1998, 2002, and 2003 (Table 1). Precipitation data were obtained from the PV and LI SNOTEL sites. Since PV lies within 2 km and at an elevation similar to the Lost Creek wetland, data from this site were assumed to represent precipitation inputs to the wetland. Data from LI were used to assess winter precipitation in the upper part of the Lost Creek watershed.

Alluvial Fan Streamflow

Streamflow along the south channel of Lost Creek was measured every 5 to 10 days at three locations (Q_1, Q_2, and Q_3) on the alluvial fan that were 200, 80, and 20 m upstream from the wetland, respectively (Figure 2). Flows at Q_1 and Q_2 were measured using 90-degree V-notch weirs, while the flow at Q_3 was measured with a cutthroat flume. Periodic calibration with a bucket and stopwatch indicated that the weirs at Q_1 and Q_2 had an accuracy of ±10%, and a similar accuracy was assumed for the discharge measurements at Q_3. Surface-water inflows to the wetland were assumed to be equal to the measured flow at Q_3. Seepage losses along the south channel of Lost Creek were calculated from the differences in discharge between Q_1, Q_2, and Q_3. The flow at all three stations was recorded within a 10-minute period, so diurnal fluctuations had no effect on the calculated seepage rates.

Table 2. Depth (cm) and soil type at the bottom of each piezometer in the Lost Creek wetland.

	Piezometer		
Nest	A	B	C
1	42 Medium to coarse sand	75 Gravelly coarse sand	
4	48 Gravelly coarse sand	66 Gravelly coarse sand	
8	40 Gravelly sand	76 Gravel	
13	40 Medium sand	72 Humic peat	100 Gravel
16	30 Gravelly coarse sand	54 Gravelly coarse sand	80 Gravelly coarse sand
17	50 Medium sand	92 Medium to coarse sand	

Alluvial Fan Ground Water

Two springs, S_1 and S_2, accounted for most of the ground water being discharged to the surface at the toe of the Lost Creek alluvial fan (Figure 2). Inflows to the wetland from S_1 and S_2 were measured by directing their flow through two small V-notch weirs. The discharge at each weir was measured with a graduated cylinder and stopwatch on the same days and similar times as the streamflow measurements. Each measurement was repeated five times, and the coefficient of variation of these measurements varied from 3% to 8%.

Two piezometers (A and B on Figure 2) were installed in early June 1997 to measure the piezometric head in the toe of the alluvial fan. These piezometers were constructed from unslotted 1.5-cm-diameter steel pipe, driven to a depth of approximately 120 cm.

Wetland Hydrology

Wetland water levels were monitored in eighteen monitoring wells installed in late June 1996 (Figure 2). The monitoring wells, which were between 0.9 m and 1.5 m deep, were installed by hand auguring to the top of a sandy gravel layer underlying the wetland. The wetland soils overlying the gravel consisted of layered deposits of sand, silt, and peat. Each well was constructed from 2.5-cm-diameter PVC pipe that was hand-slotted from the bottom of the well to the ground surface. The hole around each well was backfilled with native soil. Well locations and other key features were surveyed with a total station.

Nests of two to three piezometers were installed adjacent to wells 1, 4, 8, 13, 16, and 17 in June 1996 (Figure 2). Piezometer nest locations were selected to represent the different portions of the wetland. The piezometers, which were constructed from 1.5-cm-diameter PVC pipe open only at the bottom, were hand-driven to the desired depth. The deepest piezometer in each nest extended 5 to 10 cm into the top of the sandy gravel layer, and the other piezometers were installed at various depths in the wetland soils (Table 2).

Water levels in the wells and piezometers were measured using an electronic tape on the same days that surface-water flows were measured. Vertical hydraulic gradients (VHGs) in each piezometer nest were calculated from the difference in water levels between the deepest and shallowest piezometer. The combined error in water-level measurements and surveying measurements was estimated to be ±1 cm, so VHGs were only calculated if the water levels differed by at least 2 cm.

Hydrologic Impact of Water Diversion

Each year, the beginning of flow diversion by the Grand Ditch was signaled by a sudden and rapid decrease in flow along the south channel of Lost Creek. Wetland water-level measurements before and after this change in flow were used to assess the hydrologic impact of the diversion on the Lost Creek wetland. To assess the hydrologic effect of maintaining flow in the south channel, a small, temporary dam was used to divert flow from the north channel of Lost Creek to the south channel from 11 July until 10 September 1998. The effect of this additional inflow was assessed by comparing wetland water levels before and after the flow in the north channel had been diverted and by comparing the 1998 water-level data to the other years.

In 2003, the last year of the study, unusually high spring runoff caused a breach in the Grand Ditch several kilometers downstream from the Lost Creek head gate (Figure 1). Water from the Grand Ditch was diverted into Lost Creek and several other tributaries until the breach was repaired. Consequently, the flow in Lost Creek below the Grand Ditch continued until late July, approximately a month longer than usual, and this allowed us to further evaluate the effects of sustained summer streamflow on wetland water levels.

RESULTS

Precipitation

The peak snow water equivalent (SWE_{max}) at PV ranged from 220 mm or 80% of the mean in 2002 to

Table 3. Peak snow water equivalents (mm) at Phantom Valley (PV) and Lake Irene (LI) SNOTEL stations, and summer precipitation at PV (mm) in water years 1996, 1997, 1998, 2002, and 2003. Mean, standard deviation, and coefficient of variation are for 1981 to 2003.

	Peak SWE		Summer precipitation					
Water Year	PV	LI	May	June	July	August	Sept	Total
1996	390	950	43	33	56	30	76	238
1997	320	930	97	38	28	86	74	323
1998	250	620	15	74	69	46	20	224
2002	220	430	28	8	84	53	38	211
2003	310	770	69	15	53	76	15	228
Mean	270	750	56	36	51	52	42	236
Std. dev.	70	190	36	18	23	22	23	58
C.V. (%)	25	26	64	50	45	42	55	25

390 mm or 144% of the mean in 1996 (Table 3). The SWE_{max} values at LI were up to 140% higher than at PV due to the 510 m elevation difference, but the interannual trends were similar; the SWE_{max} at LI ranged from 430 mm or 58% of the mean in 2002 to 950 mm or 128% of the mean in 1996. Snow cover lasted until mid-May at PV and until mid- to late-June at LI in all years except 2002, when the snow pack melted almost a month earlier than usual. Summer precipitation at PV was within 5% of the mean of 236 mm in 1996, 1998, and 2003 (Table 3). In 1997 and 2002, the summer precipitation totals were 137% and 89% of the mean, respectively. June and September tended to be the driest months, but there was considerable seasonal and interannual variability in the monthly precipitation totals (Table 3).

Alluvial Fan Streamflow

Streamflow into the wetland from the south channel of Lost Creek was eliminated whenever the Grand Ditch was operating. In 1996 and 2002, the diversion period extended from early June through mid-September, so there was no streamflow into the wetland when the other hydrometric data were being collected. In 1997, 1998, and 2003, streamflows were measured between the first field measurements and the beginning of the diversion and between the end of the diversion and the last measurement date (Table 1).

In 1997, the maximum recorded flow at Q_3 prior to the start of diversion was 33 L s^{-1}. There was no streamflow into the wetland in the period from 27 June to 22 September, but streamflow then increased to almost 20 L s^{-1} as water was temporarily diverted into Lost Creek because of maintenance operations on the Grand Ditch.

In 1998, the highest measured flow at Q_3 was just 1.8 L s^{-1}, suggesting that the high flow had already occurred or that the head gate had been partially closed prior to the first measurement. Flow at Q_3 ceased following closure of the head gate on 26 June but increased to 6.0 L s^{-1} on 11 July after we diverted water into the south channel from the north channel. Flow into the wetland continued until 12 August 1998, six weeks later than in 1997.

In spring 2003, the Grand Ditch was breached and the resulting exceptionally high flows in Lost Creek overtopped the weirs at Q_1 and Q_2 and partially bypassed the flume at Q_3. Since the V-notch weir at Q_1 had a capacity of 56 L s^{-1}, the actual flow was at least 70% greater than the maximum flow measured in 1997. Flow at Q_3 ceased on 24 July after the Ditch was repaired and the head gate on Lost Creek was closed, and no flow was observed in the south channel through the end of September (Table 2).

The flow measurements indicated that there was a decrease in flow along the south channel of Lost Creek between Q_1 and Q_2 ($Q_2 = 0.89Q_1 - 0.94$, $r^2 = 0.99$, $p < 0.0001$) and between Q_2 and Q_3 ($Q_3 = 0.845Q_2 - 0.20$, $r^2 = 0.99$, $p < 0.0001$). These declines indicate that stream water was seeping into the underlying sediments and presumably recharging alluvial fan ground water. Seepage losses along the 180 m reach between Q_1 and Q_3 ranged from 0.003 L s^{-1} m^{-1} when the flow at Q_1 was 2.4 L s^{-1} to 0.07 L s^{-1} m^{-1} when the flow at Q_1 was 46 L s^{-1} (Figure 3a). On average, 29% of the flow at Q_1 was lost to seepage along the 180 m reach between Q_1 and Q_3.

Alluvial Fan Ground Water

The flow rate from spring S_1 at the toe of the alluvial fan was significantly correlated with seepage losses along the south channel of Lost Creek ($r^2 = 0.75$, $p < 0.0001$, Figure 3b). The flow from spring S_2 was also positively correlated with seepage losses, but the relationship was weaker than that for S_1 ($r^2 = 0.35$, $p = 0.164$). In 1997, the peak discharge from each spring

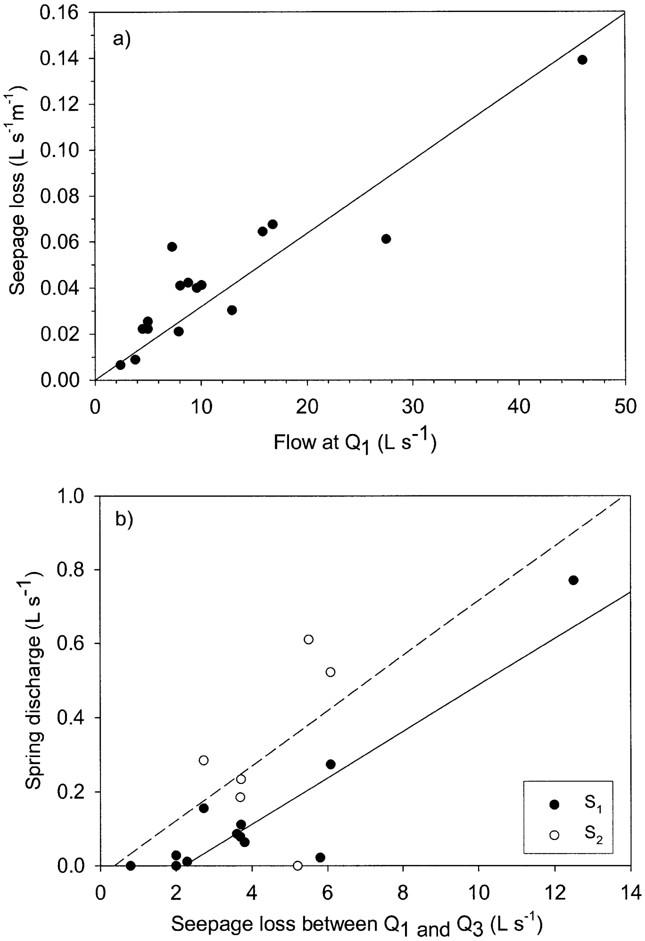

Figure 3. a) Measured seepage losses between Q_1 and Q_3 versus flow at Q_1, and b) flow from springs S_1 and S_2 versus seepage losses between Q_1 and Q_3. Solid line indicates regression line for S_1 and dashed line indicates regression line for S_2.

(0.77 L s^{-1} at S_1 on 25 June and 0.61 L s^{-1} at S_2 on 24 June) occurred within 1–2 days of the maximum observed flow at Q_3. After the diversion started on 27 June, the flow from both springs rapidly decreased; flow at S_2 ceased on 29 June and the flow at S_1 ceased on 2 July. When streamflow in the south channel resumed on 21 September, both springs began to flow again within 24 hours. In 1997, the total discharge from the two springs represented about 8% of the calculated seepage losses.

In 1998, treefall disturbed the soil around S_2 and caused the flow to become too diffuse to measure. At S_1, the highest flow recorded prior to the start of the diversion was 0.11 L s^{-1}. This is just 14% of the maximum discharge measured in 1997 and reflects the proportionally much lower SWE_{max} at LI. Our diversion of water from the north channel to the south channel caused the flow at S_1 to continue until 27 July—nearly a month longer than in 1997. Flow at S_1 did not stop until the flow at Q_3 dropped below 3 L s^{-1}.

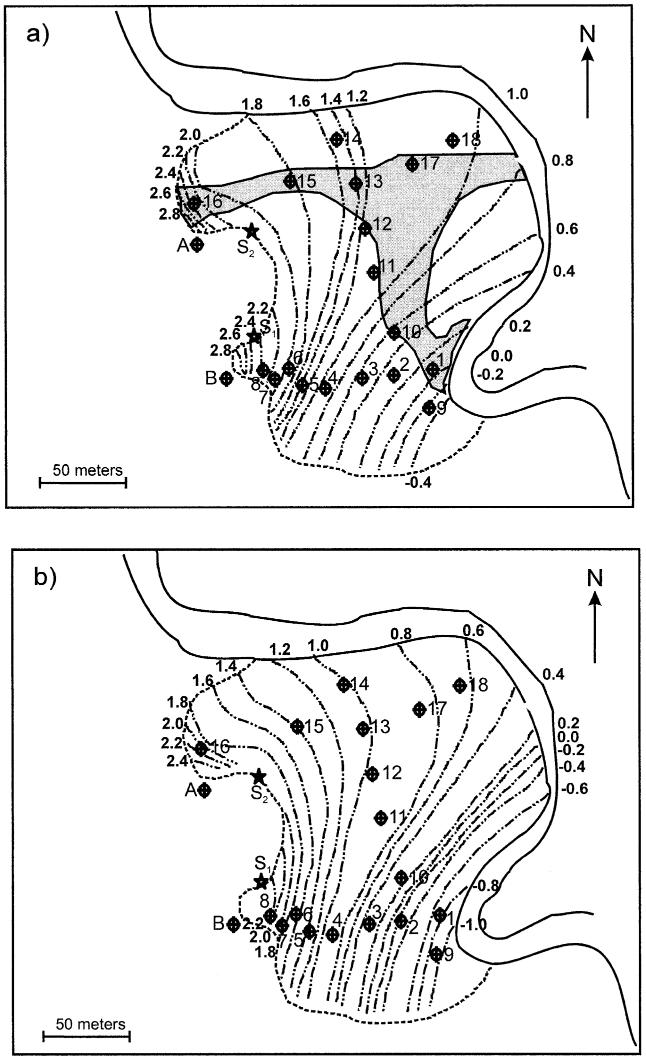

Figure 4. Water-table maps of the Lost Creek wetland at: (a) 1997 maximum water level on 19 June, and (b) 1997 minimum water level on 16 July. Shaded area in (a) indicates the extent of surface runoff. Elevations are relative to a local datum.

The piezometric heads in piezometers A and B in the toe of the alluvial fan were consistent with the observed discharge fluctuations at S_1 and S_2. Prior to the start of the diversion in 1997 and 2003, water levels in these two piezometers were more than a meter above the water table in wells 8 and 16, located less than 10 m downgradient in the adjacent wetland, indicating a steep hydraulic gradient from the fan to the wetland (Figure 4a). In both years, the piezometers went dry within 24 hours after the diversion began, indicating a decrease in head of at least 80 cm and a correspondingly sharp decrease in the upward hydraulic gradient at the toe of the fan. Once streamflow was

Table 4. Seasonal mean, maximum, and minimum water levels in the Lost Creek wetland for seven periods from June through late September in water years 1996, 1997, 1998, 2002, and 2003. ND indicates that no data are available.

	Mean Water Level Relative to Ground Surface (cm)				
Period	1996	1997	1998	2002	2003
11–15 June	ND	−2.0	−13.5	−20.6	1.1
1–3 July	−16.5	−22.1	−19.9	−42.3	1.1
16–22 July	−27.9	−38.3	−23.5	−63.4	−2.2
31 July–3 August	−33.1	−29.3	−17.9	−53.3	−21.8
21–24 August	−49.1	−20.0	−30.8	−56.5	−27.0
10–14 September	−50.7	−35.3	−51.1	−48.8	−9.5
22–27 September	−27.4	−12.7	ND	−46.7	−14.3
Maximum (cm)	−11.0	−1.4	−13.5	−20.6	1.8
Minimum (cm)	−55.8	−38.3	−51.1	−63.4	−32.5

restored, the hydraulic heads rapidly recovered to values similar to those observed before the diversion had begun. In 1998 and 2002, piezometers A and B were always dry, even in June and July 1998 when there was up to 6.0 L s^{-1} of flow at Q_3. Presumably, the reduced snow accumulation in these two years resulted in less recharge to the alluvial fan aquifer.

Wetland Water Levels and Hydraulic Gradients

The highest wetland water levels occurred in June of each year, prior to the start of the diversion of Lost Creek by the Grand Ditch (Table 4). Mean maximum wetland water levels in each year were positively correlated with the SWE_{max} values at PV and LI. In 1997 and 2003, which had above average SWE_{max} values; June water levels were at or near the surface throughout the wetland (Table 4); and there was diffuse sheet flow across at least 15% of the wetland surface (Figure 4a). In 2002, the year with the smallest SWE_{max} and an early spring melt, the diversion began earlier than usual, and streamflow in Lost Creek ceased prior to the first water-level measurement. Consequently, the mean wetland water level in mid-June 2002 was approximately 20 cm lower than in either 1997 or 2003 (Table 4).

Water levels throughout the wetland declined after the Grand Ditch began diverting water from Lost Creek (Figure 5). The most rapid decline was in the first 3 to 4 weeks after the diversion started, and the rate of decline was faster in years with less early to mid-summer precipitation. In 1997, for example, there was just 3 mm of rainfall in the first two weeks after the start of the diversion, and the mean water-level decline was 1.6 cm day^{-1}. Over the corresponding period in 1996, there was 30 mm of rainfall and the mean water-level decline was just 0.5 cm day^{-1}. In 1998, the mean water level in the wetland remained almost unchanged throughout July because the water diverted from the north channel into the south channel sustained both surface-water and ground-water inflows into the wetland. Similarly, in 2003, the mean water level in the wetland remained close to the ground surface until late July due to the late start of the diversion (Table 4).

The rate and magnitude of the water-level declines that occurred after the diversion began varied spatially as well as temporally. The largest declines were in the lower part of the wetland, which is further from the alluvial fan (wells 1, 2, 9, 14, and 18) (Figure 5). Smaller water-level declines occurred in the wetland's upper part, closer to the alluvial fan (e.g., well 5) (Figure 5). In 1997, for example, water levels in the lower part of the wetland dropped by up to 80 cm in the first two weeks after the start of the diversion. Over the same period, the average water-level decline in wells 3 through 8, nearer the toe of the fan, was just 15 cm.

The vertical hydraulic gradients (VHGs) in the six piezometer (PZ) nests indicated that the spatial variability in water-level declines was at least partly due to differences in the amount of ground-water recharge. In PZ nests 4, 8, 13, and 16, in the upper part of the wetland, the VHGs were mostly upward, indicating ground-water discharge into the wetland, and the water-level declines were relatively small (Figure 6). Prolonged rainfall in late July and early August in both 1996 and 1997 temporarily increased the total head in the shallow piezometer at nest 13 in the middle part of the wetland. This rain had little effect on water levels in the deeper piezometer, resulting in a transient downward gradient at PZ nest 13. Similarly, there were strong downward VHGs in PZ nests 1 and 4 in July and August 2003 because the continuing surface-water inflows maintained a high hydraulic head in the shallow piezometer while total head in the deep piezometer decreased.

In the lower part of the wetland, where the water-level declines were greatest, the VHGs in PZ nests 1

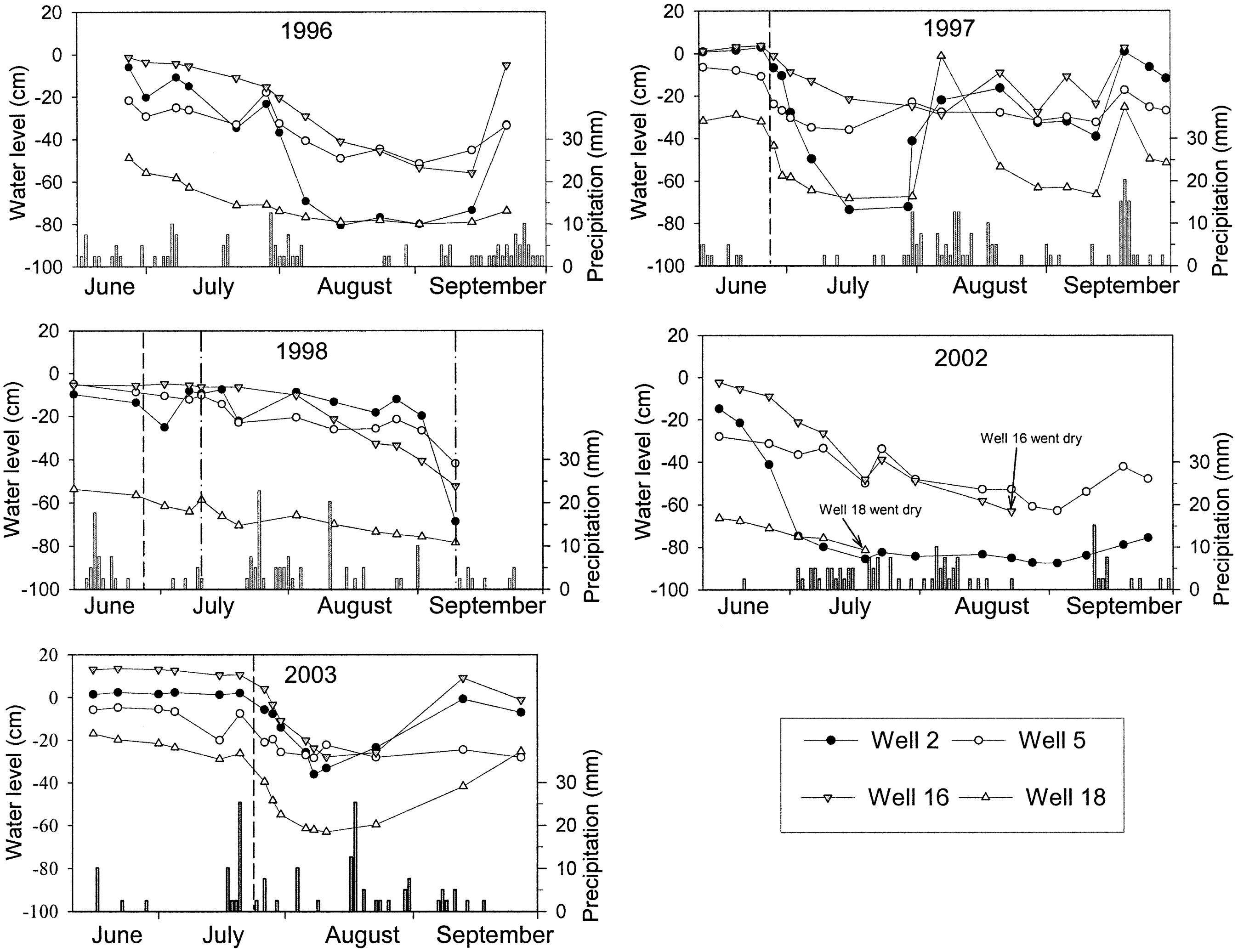

Figure 5. Water levels relative to ground surface in wells 2, 5, 16, and 18 and daily precipitation at PV in 1996, 1997, 1998, 2002 and 2003. Vertical dashed lines indicate when the diversion began in 1997, 1998, and 2003. In 1996 and 2002, the diversion began before the first water-level data were collected. Vertical dash-dot lines in 1998 indicate when diversion of water from the north channel to the south channel started and ended.

and 17 were predominantly downward, indicating that ground water was moving from the wetland into the underlying gravel layer and presumably discharging to the Colorado River (Figure 6). Occasional upward gradients in these piezometer nests occurred in June and early July in years with a large snowpack (e.g., 1997 and 2003) and in late September 1997 when streamflow in Lost Creek was temporarily restored. In these periods, the hydraulic head increased more rapidly in the deeper piezometer than in the shallow piezometer, indicating a close hydrologic connection between the gravel layer underlying the wetland and the adjacent alluvial fan.

Seasonal minimum water levels generally occurred in August and September, when the diversion was operating, and following periods with little or no precipitation (Figure 5). However, the lowest mean minimum water level was −63 cm in mid-July 2002, when there was a below average snowpack, an early start to the diversion, and only 8 mm of precipitation in June (Tables 3, 4; Figure 5). The highest mean minimum water level was −33 cm in late August 2003, a year that had an above average snowpack, a late start to the diversion, and above average precipitation in July and August.

Due to the generally steep topography, the overall flow direction was similar at both low and high water levels. However, the horizontal gradient was steepest at the seasonal minimum (Figure 4b). Water levels in all of the wells were always higher than the Colorado River, indicating that the entire wetland was draining toward the Colorado River.

Wetland water levels increased in late summer in each year except 1998 due to the restoration of flow

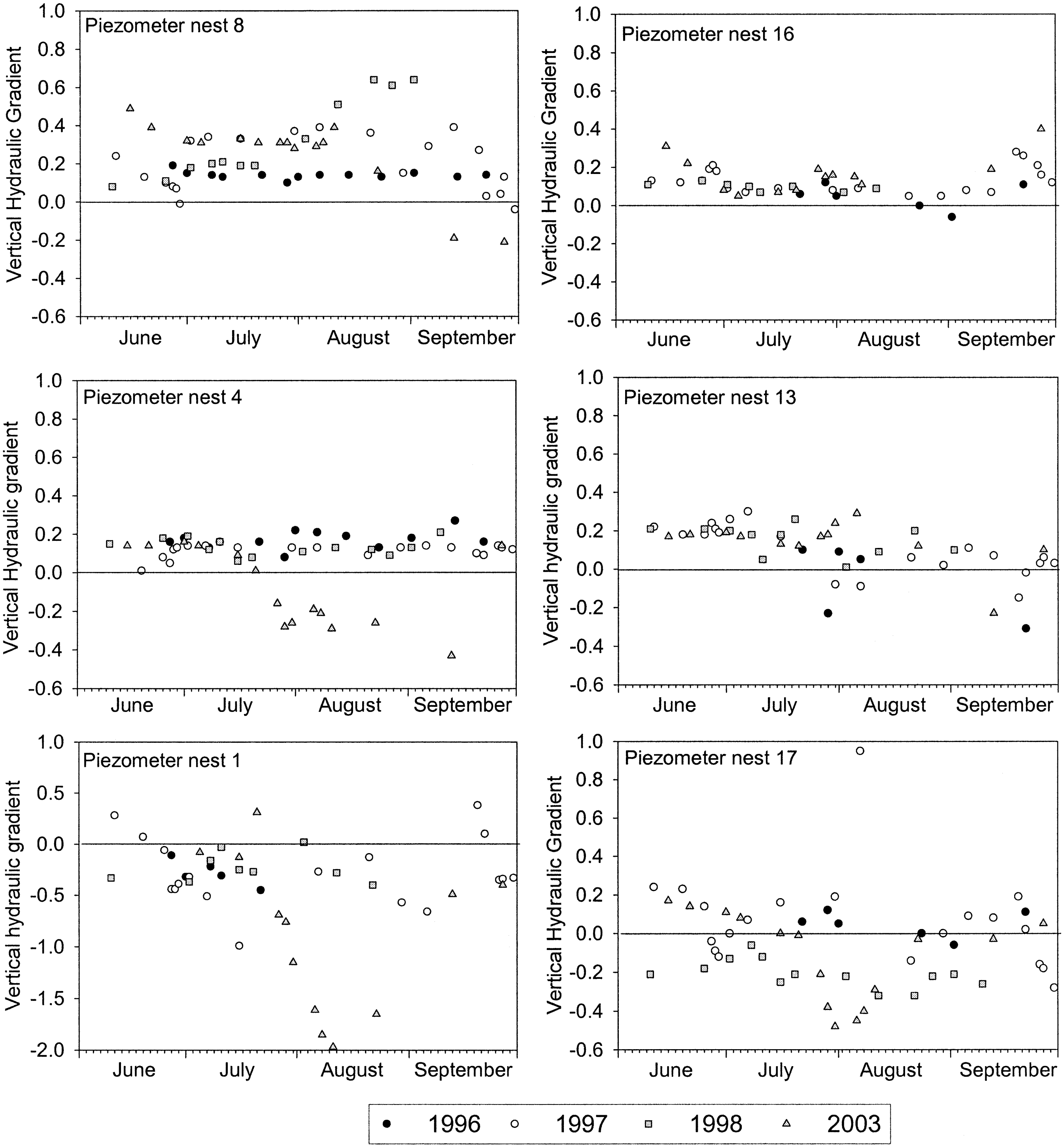

Figure 6. Vertical hydraulic gradients (VHGs) in piezometer nests adjacent to wells 1, 4, 8, 13, 16, and 17 in 1996, 1997, 1998, and 2003. The shallow piezometers were mostly dry in 2002, so no VHG data are available. The gradients shown are between the deepest and the shallowest piezometer in each nest. Positive gradients are directed upwards. Nest 8 and 16 are in the upper part of the wetland, nests 4 and 13 are in the middle part of the wetland, and nests 1 and 17 are in the lower part of the wetland.

in Lost Creek following the end of the diversion and the seasonal increase in the precipitation to evapotranspiration ratio (Figure 5). For example, in mid-September 1997, the mean wetland water level increased by 32 cm in less than 7 days after flow had resumed in the south channel of Lost Creek. The largest increases during this period were in the lowest portion of the wetland (wells 1 and 2), while much smaller increases were observed in the upper part of the wetland near the toe of the alluvial fan (e.g., wells 8 and 16). These increases were facilitated by the 53 mm of precipitation that fell over this 7-day period. However, water levels in the lower part of the wetland dropped rapidly after Lost Creek stopped flowing on 26 September, indicating that the water-level increase was primarily due to the temporary restoration of surface water inflows.

DISCUSSION

Alluvial Fan Stream—Ground-Water Interactions

Alluvial fans are hydrologically dynamic landforms where surface water and ground water are often closely connected (Shimada et al. 1993, Herron and Wilson 2001, Houston 2002). Three lines of evidence point to a close connection between surface water and ground water in the Lost Creek alluvial fan. First, the south channel of Lost Creek lost almost 30% of its flow to seepage between the upper and lower gauging stations, and this water must have been moving downward into the coarse sediments of the alluvial fan. Similarly high seepage rates, representing as much as 70% of streamflow, have been observed in other alluvial fans (Houston 2002). Second, there were strong linear relationships between streamflow in Lost Creek and the seepage rate from the springs at the toe of the fan. Third, the heads in piezometers A and B in the alluvial fan dropped almost immediately when the diversion dewatered the south channel of Lost Creek, and recovered rapidly once flow resumed. These observations indicate that seepage from the south channel of Lost Creek is the primary source of recharge to the alluvial fan aquifer.

Previous studies of the linkages between surface water and ground water in alluvial fans have often used a tracer-based hydrochemical approach (e.g., Shimada et al. 1993), and a similar approach would have been a valuable supplement to the hydrometric techniques used in this study. However, preliminary analyses showed that stream water and alluvial fan ground water at the Lost Creek site have almost identical $\delta^{18}O$ signatures (C. Westbrook, unpublished data). The use of dyes or chemical tracers was not permitted at the study site due to National Park regulations.

Alluvial Fan—Wetland Hydrologic Interactions

The strong hydrologic connection between the Lost Creek alluvial fan and the adjacent wetland is largely due to the fact that streamflow is the primary water source for parts of the wetland. When the Grand Ditch was not diverting water from Lost Creek, stream water flowed into the wetland and formed areas of shallow sheet flow and standing surface water. Streamflow inputs typically exceeded ground-water inflows from the two springs at the base of the fan by more than an order of magnitude, and they were also greater than precipitation inputs in the periods when there was streamflow into the wetland. For example, the minimum observed streamflow of 1.8 L s^{-1}, which was observed in late June 1998, corresponds to a wetland recharge rate of almost 10 mm day^{-1} when distributed across the 1.6 ha wetland area and a higher recharge rate when distributed across the smaller portion of the wetland that received streamflow inputs. This means that streamflow inputs in June 1998 were at least four times greater than the average precipitation of 2.5 mm day^{-1}. In June 1997, the highest recorded streamflow of 33 L s^{-1} exceeded the average daily precipitation (1.3 mm day^{-1}) by more than two orders of magnitude. Although ground water and precipitation contribute water to the Lost Creek wetland, stream water is clearly the dominant water source in many areas. This represents a departure from the general model of slope wetland hydrology, which suggests that slope wetlands are almost exclusively supported by ground-water inflows (Brinson 1993). We hypothesize that slope wetlands in similar hydrogeologic settings to the one at Lost Creek are likewise at least partially dependent on stream inflows.

In those parts of the Lost Creek wetland that do not receive stream inflows, water levels must be maintained by a combination of ground-water and precipitation inputs. Seepage from Lost Creek and the resulting ground-water discharge provide an additional linkage between the alluvial fan and the wetland. Ground-water inflows to the wetland occur as spring flow at the toe of the fan and an upward ground-water flux into the upper part of the wetland. Due to the importance of stream seepage as a ground-water-recharge source, spring flow was eliminated following the start of the diversion, making it ineffective for maintaining wetland water levels. However, diffuse ground-water seepage into the upper part of the wetland continued at a reduced rate even after streamflow was eliminated, thereby limiting the water-level declines to less than 40 cm. Areas further from the fan did not receive this ground water, and water-level declines were correspondingly greater. These results are consistent with previous studies, which show that wetland water-level fluctuations are progressively moderated as ground-water inputs increase (Siegel 1988, Roulet 1990, Winter and Rosenberry 1995, Devito et al. 1996, Hunt et al. 1999).

Effect of Precipitation on Wetland Water Levels

In the Rocky Mountain region, the annual cycle of snow accumulation and melt is the dominant control on runoff and streamflow. Snowmelt contributes to wetland recharge directly by in-situ melt and indirectly by generating surface-water and ground water runoff (Windell et al. 1986, Bachmann 1994). Early summer water levels in the Lost Creek wetland were higher in years with a larger winter snowpack. Variability in the duration of these high water levels indicates that they were caused by increased surface-water and ground-water inflows, rather than by more in-situ melt. For example, 1997 and 2003 had similarly large snow packs, and mean water levels were at or near the surface in mid-June of both years. In 1997, streamflow inputs were eliminated, and ground-water inputs to the wetland were much reduced following the start of the diversion in late June. As a result, the mean water table in the wetland dropped by 36 cm between mid-June and mid-July. During the same period in 2003, Lost Creek was not being diverted, streamflow and ground-water inputs continued, and the mean water table dropped by just 3 cm.

Summer precipitation in the central Rocky Mountains is highly variable (Hauer et al. 1997) but can play an important role in controlling wetland water levels during the growing season (Cooper 1990, Bachmann 1994). At our study site, increased precipitation in the period following the start of the diversion of Lost Creek reduced but did not eliminate the water-level declines. Wetland water levels rose sharply in August 1997 when the monthly precipitation total was 1.5 standard deviations above the mean, but mid- to late-summer precipitation had little or no effect on water levels in normal to dry years. Presumably, in most years, much of the mid- to late-summer precipitation is used to satisfy soil moisture deficits rather than producing additional wetland recharge. The implication is that while summer precipitation contributes to the wetland water budget, continued stream and ground-water inflows are necessary to maintain wetland water levels during the growing season.

Water Diversion Impacts and Restoration Potential

Water diversions can reduce water levels in riparian wetlands (Kondolf 1987, Ruddy and Williams 1991) with consequent adverse impacts on riparian vegetation (Harris et al. 1987, Smith et al. 1991). However, there is no information on the impacts of water diversions on slope wetlands. Since surface water and ground water are directly connected in the Lost Creek alluvial fan, any reduction in streamflow due to the diversion leads to substantial water-level declines throughout the wetland, even in areas receiving ground-water inflows. Water-level declines occurred in both wet and very dry years, suggesting that water-level reductions have occurred each year since the Grand Ditch was constructed in the late 1800s. The impact of the diversion on wetland water levels generally will be less in wet summers because the additional rainfall can help sustain wetland water levels. In dry years, the effect of the Grand Ditch diversion is proportionally larger because summer precipitation events have little to no effect on wetland water levels.

There are no streamflow inputs to the wetland for most of the summer because of the dewatering of Lost Creek by the Grand Ditch. However, undiverted streams in the Upper Colorado River watershed with drainage areas similar to Lost Creek are perennial, suggesting that in the absence of the Grand Ditch, streamflow and ground-water inputs from the Lost Creek alluvial fan would continue to be the primary source of water to the wetland throughout the summer in all but the driest years. This is supported by the measurements in summer 2003, when the Grand Ditch was not in operation and wetland water levels remained high well into the growing season. While water levels in nearby undisturbed slope wetlands probably show seasonal declines because PET exceeds precipitation for much of the summer, the water-level declines induced by the Grand Ditch are almost certainly greater than the natural range.

The effect of the diversion induced water-level declines on wetland soils and vegetation cannot be assessed directly because there are no pre-diversion data. However, water-level declines of 20 to 30 cm below the surface for more than 2 to 3 weeks caused a negative carbon balance in peatlands in the upper Colorado River valley (Chimner and Cooper 2002). This implies that the peat deposits near wells 6 to 8 and well 11 are not sustainable under the present hydrologic regime. Upland plants, such as *Trifolium repens* L. and *T. pratense* L. are present in the northern part of the Lost Creek wetland (D. Cooper, unpublished data), and the presence of these plants indicates a possible adverse effect of the altered hydrologic regime. Other studies have documented substantial changes in wetland soils and vegetation after prolonged periods of imposed water-level declines (e.g., Bernaldez et al. 1993, Suso and Llamas 1993).

Mid- to late-summer water levels in the Lost Creek wetland could be increased substantially by re-establishing summer flows in Lost Creek. The experimental diversion of water from the north channel to the south channel in 1998 showed that a flow of 6 L s^{-1} at Q_3 caused wetland water levels in mid-July to be 40 cm higher than in years such as 2002, which had a similar SWE_{max} and slightly lower summer precipitation but lacked the inflows from the north channel. The equations used to calculate seepage indicate that a flow of 9 L s^{-1} at Q_1 is needed to sustain a flow of 6 L s^{-1} at Q_3. Field observations show that the section of Lost Creek between the Ditch and the apex of the alluvial fan is gaining. Therefore, if 9 L s^{-1} were released from the Grand Ditch into Lost Creek, one would expect a similar or larger flow at $Q_{1,}$ and a flow of at least 6 L s^{-1} at Q_3. Maintaining a flow of 9 L s^{-1} in Lost Creek for a 3-month period from mid-June to mid-September by releasing flow from the Grand Ditch would require 70,000 m^3 of water, less than 0.3% of the mean annual water yield of the Grand Ditch. In a dry year, the amount of water needed to sustain the wetland inflows at Lost Creek would be proportionally larger but would still represent only 1% of the water diverted by the Grand Ditch. Thus, a relatively small amount of water could substantially improve the hydrologic conditions in this wetland and potentially minimize the adverse effects on soils and vegetation.

The Grand Ditch diverts the flow of twelve other headwater tributaries of the Colorado River in addition to Lost Creek. All of these streams have alluvial fans where they reach the main valley floor, and many of the fans have adjacent slope wetlands. We focused on Lost Creek because 90% of the drainage area is above the Ditch and because the small size of the alluvial fan—wetland complex facilitated a detailed hydrologic study. More limited streamflow and water-level data have been collected from the nearby Red Creek alluvial fan—wetland complex, which is considerably larger than the Lost Creek system (Woods 2000). Data from the Red Creek site indicate that the Grand Ditch is having a comparable effect on streamflow and wetland water levels, particularly during dry summer periods. This suggests that the impacts observed at Lost Creek occur in other alluvial fan slope wetlands downstream from the Grand Ditch. The broader implication is that the adverse hydrologic effects of streamflow diversions are not limited to the adjacent riparian zones but can extend into nearby wetlands where the hydrologic connections are much less obvious and poorly understood.

CONCLUSIONS

This study used hydrometric data and the fluctuations in streamflow created by a seasonal water diversion to understand the hydrology of the Lost Creek alluvial fan-wetland complex in Rocky Mountain National Park. Stream seepage on the alluvial fan is the primary source of recharge for ground water in the alluvial fan aquifer. Summer water levels in the adjacent slope wetland are supported by a combination of streamflow and ground-water discharge from the alluvial fan, with summer precipitation playing a minor role. Water-level fluctuations are greatest in dry years and in the lower portion of the wetland where there is little or no upward ground-water flow from July through September. The importance of streamflow as a wetland water source represents a departure from the present conceptual model of slope wetlands, which assumes that ground water is the primary water source. The seasonal elimination of streamflow by the diversion results in substantial declines in wetland water levels, particularly in the lower portion of the wetland. Slope wetlands in settings comparable to the Lost Creek wetland are likely to be similarly vulnerable to upstream water diversions. An understanding of the hydrology of these alluvial fan slope wetlands is essential to their protection and management.

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