DISSERTATION

ECOHYDROLOGY OF SUBALPINE WETLANDS IN THE KAWUNEECHE VALLEY, ROCKY MOUNTAIN NATIONAL PARK, COLORADO

Submitted by

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in partial fulfillment of the requirements
for the degree of Doctor of Philosophy
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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY SCOTT W. WOODS ENTITLED ECOHYDROLOGY OF SUBALPINE WETLANDS IN THE KAWUNEECHE VALLEY, ROCKY MOUNTAIN NATIONAL PARK, COLORADO BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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ABSTRACT

ECOHYDROLOGY OF SUBALPINE WETLANDS IN THE KAWUNEECHE VALLEY, ROCKY MOUNTAIN NATIONAL PARK, COLORADO

Wetlands in the central Rocky Mountains depend on surface water or groundwater inflows, so they are vulnerable to hydrologic modifications such as water diversions. However, a paucity of hydrologic studies limits the ability of resource managers to assess the impacts of diversions on central Rocky Mountain wetlands. This study addressed three issues regarding the effect of an existing diversion on subalpine wetlands in the Kawuneeche Valley in Rocky Mountain National Park. The concerns were: 1) reduced flow in the Colorado River is lowering the water table in riparian wetlands, 2) lowering of the water table is reducing willow seedling establishment by limiting soil water availability, and 3) the diversion of tributary streams is reducing water levels in alluvial fan toeslope wetlands.

Linear regression analyses indicated that the effect of Colorado River stage on water table levels decreased with distance from the river. The effect of the Colorado River was greatly reduced in narrow valley sections and areas near beaver ponds and oxbows. A numerical groundwater model indicated that the diversion was lowering the water table by 0.01 to 0.12 m, with the greatest reductions in areas near the Colorado River in mid-July.

A split-split plot experiment indicated that decreases in mean soil water content due to lowering of the riparian water table ranged from <4% in higher-elevation sand plots to about 15% in lower-elevation gravel plots. Although willow seedling survival was positively correlated with soil water availability, these declines in soil water content

had little effect on seedling survival. However, the reductions in high flows due to the diversion may be reducing the area of bare sediment needed for establishment.

A detailed hydrologic study of the Lost Creek alluvial fan toeslope wetland indicated that flow in Lost Creek and seepage at the toe of the fan provided more than 90% of the early summer wetland inflows. Seepage from Lost Creek sustained water levels in the alluvial fan aquifer, and this aquifer sustained groundwater flow into the wetland. The close connection between streamflows and groundwater in alluvial fan toeslope wetlands indicates that diversions can adversely affect wetlands that are not immediately adjacent to the stream.

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Finally, and most importantly, I want to thank my family for their unconditional love, support and encouragement.

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Rivers, I suppose, are not at all like human beings, but it is still possible to make apt comparisons, and this is one: Understanding, whether instinctive and immediate or developing naturally through time or grown by conscious effort, is a necessary preliminary to love. Understanding of another human being can never be complete, but as it grows towards completeness it becomes love almost inevitably. One cannot know intimately all the ways and movements of a river without growing into love of it. And there is no exhaustion to the growth of love through knowledge, whether the love be for a person or a river, because the knowledge can never be complete. One can come to feel in time that the whole is within one's compass, not yet wholly and intimately known, but there will always be something ahead, something more to know.

R. Haig Brown
A River Never Sleeps

DEDICATION

This dissertation is dedicated to my dear parents,

Irene and Bill

for a lifetime of unwavering support and unconditional love,

and to my son,

Rylan

for the gift of your smile.

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1. INTRODUCTION

The central Rocky Mountains of the western United States have a continental climate characterized by cold winters and warm, dry summers (Siemer, 1977). Winter precipitation falls as snow, and most of the annual runoff occurs during spring snowmelt. Summer precipitation occurs primarily as brief, convective thunderstorms, and there are often periods of several weeks with no rain. Evapotranspiration rates usually exceed precipitation throughout the summer. Consequently, wetlands in the central Rocky Mountains are limited in spatial extent, and only occur in landscape positions where they receive surface water or groundwater inflows (Cooper, 1990). Most are either riparian wetlands along montane and subalpine streams, or toeslope wetlands at the foot of hillslopes.

The dependence of central Rocky Mountain wetlands on surface water and groundwater inflows means that they are potentially vulnerable to man-made hydrologic modifications such as ditches, drains and water diversions. In recent years there has been a substantial increase in the population of the central Rocky Mountain region (U.S. Census Bureau, 2000). This rapid population growth has resulted in increasing pressure to supplement existing water supplies by diverting more water from streams flowing out of the Rocky Mountains. However, most of the region's streams are already heavily appropriated. Colorado in particular has numerous stream diversions that withdraw water from mountain streams and transport it to the region's more densely populated areas (Petsch, 1985). There is concern that existing and future withdrawals from central Rocky Mountain streams could adversely affect the region's wetlands. However, a lack of hydrologic studies in central Rocky Mountain wetlands currently limits the ability of water resource managers to assess and predict the effects of water diversions.

RIPARIAN WETLANDS IN THE CENTRAL ROCKY MOUNTAINS

Riparian wetlands in the central Rocky Mountains typically occur in broad alluvial valleys along unconfined montane and subalpine streams. These high-elevation riparian wetlands are substantially different from those at lower elevations, both in terms of their dominant vegetation and their hydrologic regime. Low- to mid-elevation riparian systems in the central Rocky Mountain region are largely dominated by cottonwoods (*Populus deltoides* and *P. angustifolia*). In high-elevation riparian systems, cottonwoods are replaced by willows (*Salix* spp.), and these often form dense shrublands covering the entire valley bottom.

While low- to mid-elevation riparian systems depend primarily on stream water as the primary water source, high-elevation riparian wetlands are also supported by runoff from hillslopes, in-situ snowmelt and summer rainfall (Ruddy and Williams, 1991; Sundeen et al., 1989). The availability of water from these other sources can make it difficult to distinguish between riparian wetlands and other types of wetlands on the valley floor (Patten, 1998).

In the relatively confined sections of a high-elevation stream valley, surface and subsurface hillslope runoff may support water levels across the entire valley floor. In such situations the importance of the stream for supporting riparian vegetation is limited to its role as an agent for geomorphic disturbance. Conversely, studies in other areas have shown that streamwater can be an important source of recharge to the alluvial aquifer

(Stanford and Ward, 1988). In such cases, the diversion of streamflow could reduce water levels in adjacent riparian wetlands.

One of the potential impacts of lowering the water table level in riparian wetlands is to reduce seedling establishment. Successful establishment of many riparian tree and shrub species depends on the presence of moist, bare substrate when seed dispersal occurs (Auble et al., 1997; Scott et al., 1996, 1997; Auble and Scott, 1998). The probability that an individual seed will germinate depends largely on how much soil water is available (Fenner et al., 1984; Sacchi and Price, 1992). Germination rates in willows along the Tanana River in Alaska were positively correlated with soil water availability (Krasny et al., 1988). Close to 100% mortality rates occurred in arroyo willow (*Salix lasiolepis*) seedlings that were not watered compared to seedlings that were watered (Saachi and Price, 1992). Supplemental watering increased the recruitment from seed of felt-leaf willow (*Salix alaxensis*) on abandoned placer mine tailings in interior Alaska (Cooper and van Haveren, 1994).

Even after germination, seedlings remain dependent on soil water until they can extend roots to the water table (Segelquist et al., 1993). Survival rates increase rapidly as plants become older and the root system develops (McLeod and McPherson, 1973; Saachi and Price, 1992). However, some riparian species do not become phreatophytic until they are several years old. Fremont cottonwood *(Populus deltoides)* seedlings along the Yampa River in western Colorado did not use groundwater until they were three or four years old (Cooper et al., 1999).

Soil water availability in riparian soils is primarily a function of the depth to the water table, soil texture, and the frequency of rainfall. Along lower elevation rivers in the

Rocky Mountain region, summer rainfall is very infrequent and soil water recharge depends almost entirely on the occurrence of high flows, which cause flooding and raise the water table to near the ground surface. By reducing or eliminating high flows, flow regulation on lowland rivers can reduce or eliminate the zone where conditions are suitable for establishment (Rood and Mahoney, 1990, 1995).

Most of the establishment of riparian shrubs from seed along high-elevation streams in the Rocky Mountains occurs on gravel bars immediately adjacent to the stream. The extent to which flow depletion is likely to affect soil water availability and seedling establishment in these gravel bars depends on the relative importance of the water table versus summer rainfall for controlling soil water content. In Alaska, studies have suggested that soil water availability may not always be a limiting factor for willow seedling establishment on gravel bars because of frequent summer rainfall (Douglas, 1995). However, direct comparisons between Alaskan streams and Rocky Mountain streams may be inappropriate due to differences in the amount and timing of summer rain. Until now, no work has been done to understand the relative importance of water table depth and rainfall for controlling soil water availability and willow seedling establishment on gravel bars along high-elevation, central Rocky Mountain streams.

TOESLOPE WETLANDS IN THE CENTRAL ROCKY MOUNTAINS

Toeslope wetlands occur on or at the foot of slopes, particularly around the margins of alluvial fans. Their position in the landscape suggests that these toeslope wetlands are supported primarily by hillslope runoff. Many toeslope wetlands in the central Rocky Mountains are fens (Cooper, 1990). These fens are ecologically important for two reasons. First, they are among the most southerly boreal peatlands in North America (Malterer, 1996). Second, they are older than most other boreal peatlands; many have basal carbon dates of between 8000 and 12000 YBP (Chimner, 2000). Since peat accumulation rates are related to temperature, the stratigraphy of central Rocky Mountain fens provides a valuable record of climate change during the Holocene.

The steep topographic gradient upslope from toeslope wetlands suggests that outflow rates are very rapid, making these wetlands extremely vulnerable to any reduction in inflows due to hydrologic modifications or climate change. However there have been virtually no hydrologic studies of toeslope wetlands in the central Rocky Mountains. Given the increased pressure on water resources in the Rocky Mountains there is an urgent need to understand the hydrology of toeslope wetlands, and hence the potential impacts of water diversions on these types of wetlands.

PURPOSE AND OBJECTIVES OF STUDY

The overall purpose of this study was to determine the effects of one of the oldest and largest water diversions in Colorado, the Grand Ditch, on the hydrology and ecology of subalpine wetlands in the Upper Colorado River headwaters in Rocky Mountain National Park (RMNP), Colorado. The Grand Ditch was constructed in the late 1800s to divert up to 10 m^3/s of water for farms on the east side of the Continental Divide. The Ditch traverses the eastern slope of the Never Summer Mountains, and intercepts the flow of eleven headwater tributaries of the Colorado River. Headgates on each tributary are used to divert the streamflow into the Ditch. Although there is some interannual variability due to the timing of the snowmelt, the diversion usually operates between mid-

May and mid-September. The Grand Ditch is of particular concern because the Colorado River headwaters contain some of the largest remaining subalpine wetland complexes in Colorado.

The study addressed three specific concerns about the effects of the Grand Ditch on the ecohydrology of subalpine wetlands within RMNP. The first concern is that reduced flows along the main stem of the Colorado River are reducing water table levels in the adjacent riparian wetlands. Chapter 2 presents the results of a three-year study to quantify stream-groundwater interactions along a 1.4-km reach of the Colorado River in RMNP. The objectives were to: i) quantify the effect of the Grand Ditch on flow and stage in the Colorado River, ii) understand the extent of stream-groundwater interactions between the Colorado River and the adjacent alluvial aquifer, and, iii) determine whether reductions in Colorado River flow and stage result in lower water table levels in the adjacent riparian wetlands.

A closely related concern is that reduced streamflow along the Colorado River has reduced willow establishment rates on gravel bars and other riparian areas. Field observations indicated that there are abundant mature willow stands along the Colorado River in RMNP, but a lack of willow regeneration in the riparian zone. Chapter 3 presents the results of a field experiment to investigate the effects of elevation, soil texture, and precipitation on soil water availability and willow seedling establishment along a 200-m subalpine reach of the Colorado River in RMNP. The objectives were to: 1) determine whether willow seedling establishment is limited by soil water availability, 2) determine the effects of elevation, soil texture, and simulated rainfall on soil water availability and seedling establishment, 3) quantify the effect of the Grand Ditch on streamflow, stage and water table levels along the study reach during the growing season and hence, 4) evaluate whether the observed lack of willow regeneration can be attributed to streamflow depletion by the Grand Ditch.

The third concern related to the hydrologic effect of the Grand Ditch is that the diversion of tributary streamflow has reduced surface water and stream-fed groundwater inflows to toeslope wetlands. Toeslope wetlands around the margins of tributary alluvial fans may be particularly vulnerable to diversions such as the Grand Ditch. Reductions in tributary streamflow may cause a decline in water levels in these alluvial fan toeslope wetlands during the summer months. A decline in water levels could result in a loss of wetland species. In toeslope wetlands that are fens a decline in water levels is likely to reduce the rate of peat accumulation, or even cause a net loss of peat through increased oxidation (Chimner, 2000). Chapter 4 reports on a two-year study of the Lost Creek alluvial fan toeslope wetland in RMNP. The objectives were to: i) determine the hydrologic regime of the study wetland under the current hydrologic conditions; ii) estimate the wetland inflows that would occur in the absence of the Grand Ditch; and iii) determine the effect of the Grand Ditch on water levels in the Lost Creek toeslope wetland.

The paucity of similar studies means that these three papers provide a unique and innovative understanding of the ecohydrology of subalpine wetlands in the central Rocky Mountains. This information is critical to anyone who is concerned with the potential environmental impacts of water diversions on subalpine wetlands in the central Rocky Mountains.

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2. STREAM – GROUNDWATER INTERACTIONS ALONG A SUBALPINE REACH OF THE COLORADO RIVER, ROCKY MOUNTAIN NATIONAL PARK, COLORADO.

ABSTRACT

Many streams in the central Rocky Mountains are affected by water diversions. There is concern that these diversions could adversely affect riparian vegetation by lowering the water table in alluvial aquifers. However little work has been done to quantify stream-groundwater interactions along central Rocky Mountain streams. This paper reports on a three-year study along a 1.4 km subalpine reach of the Colorado River to: 1) quantify the interactions between the Colorado River and the adjacent alluvial aquifer, and 2) determine whether an existing streamflow diversion is lowering the water table in the alluvial aquifer.

Linear regression analyses of the relationship between river stage and water table levels in 27 wells indicated that the effect of the Colorado River on water table levels decreased with distance from the river. Hillslope runoff was more important than the Colorado River for controlling water table levels in confined valley sections. The strength of the relationship between river stage and water table levels varied depending on the proximity of beaver ponds and oxbows.

A calibrated numerical groundwater model indicated that the predominant direction of groundwater flow was down-valley. Consequently, between 4% and 50% of the total runoff from the watershed occurred by subsurface flow in the alluvial aquifer. Hillslope groundwater discharge was typically less than 12% of the down-valley component of flow. There was a large and dynamic exchange of water between the alluvial aquifer and the Colorado River, with leakage into the alluvial aquifer ranging

from 0.08 to 0.22 m^3/s, and discharge to the river ranging from 0.15 to 0.27 m^3/s. The modeled net flux ranged from a gain of 0.2 m^3/s in June 1997 to a loss of 0.04 m^3/s in August 1996.

The modeled water table declines in the alluvial aquifer due to the diversion ranged from 0.01 m to 0.12 m. The maximum declines were in mid-July, in wells near the Colorado River. Smaller declines were predicted earlier and later in the year, and in wells further from the river. Declines of 0.12 m or less are unlikely to adversely affect mature, deeply rooted riparian trees and shrubs. Changes may have occurred in the species composition of the shallow-rooted herbaceous understory.

Keywords: stream – groundwater interactions; riparian wetlands; streamflow diversions; central Rocky Mountains; Rocky Mountain National Park.

INTRODUCTION

Interactions between streams and alluvial aquifers are controlled primarily by the geomorphic and geological characteristics of the stream and its watershed. Along laterally confined, low-order streams in mountainous watersheds there is a steep hydraulic gradient from the alluvial aquifer to the stream. The resulting groundwater discharge results in a downstream increase in flow, so the stream is said to be gaining. For such streams changes in stage have little effect on the adjacent water table.

The hydraulic gradient from the alluvial aquifer to the stream along unconfined reaches of higher order streams is usually much smaller than in confined, headwater streams. Consequently, during high flows water may flow from the stream and into the adjacent aquifer (Squillace et al., 1993). This bank storage effect temporarily increases water levels in the alluvial aquifer, but as flow decreases the stored water is discharged back into the stream (Winter et al., 1999). In higher-order unconfined rivers with large stage changes, pulses of groundwater recharge generated by high streamflows can be transmitted through the alluvial aquifer for several kilometers (Sophocleus, 1991; Vekerdy and Meijerink, 1998), and may be critical for maintaining high water table levels in riparian areas and wetlands (Hurr, 1983).

In some environments, such as on alluvial fans and in arid areas where the water table is below the bed of the stream, the hydraulic gradient is from the stream to the aquifer. There is a net loss of flow in the downstream direction, so the stream is said to be losing. In arid and semi-arid areas losing streams may be the primary source of recharge to the alluvial aquifer. Consequently any reduction in streamflow can result in lowering of the water table near the stream. Phreatophytic riparian trees and shrubs along losing streams are therefore more vulnerable to reduced flows below dams and diversions than those along gaining streams (Kondolf et al., 1987).

Lowering of the alluvial water table can increase water stress and reduce seedling survival in riparian phreatophytes (Mahoney and Rood, 1991; Smith et al., 1991; Tyree et al., 1994). The decline of riparian cottonwood (*Populus* spp.) communities below several dams in the western United States and Canada has been attributed in part to lowering of the water table due to a reduction in streamflow (Rood and Heinz-Milne, 1989; Rood and Mahoney, 1990; Busch and Smith, 1995; Rood et al, 1995). Lowering of the water table can also adversely affect floodplain wetlands that depend on saturated, anaerobic soils to prevent the invasion of upland plant species (Stromberg et al., 1996).

In the central Rocky Mountain region of the semi-arid western U.S. streams and alluvial aquifers provide an important water source for human use as well as for riparian areas and wetlands. Rapid population growth in and adjacent to the central Rocky Mountains has resulted in increasing pressure to use more of the water from mountain streams to supplement existing water supplies. However, most of the region's streams are already heavily appropriated (Petsch, 1985). There is concern that withdrawals from Rocky Mountain streams by existing and future water diversion projects could lower alluvial water tables, and thus adversely affect riparian areas and wetlands. In order to determine whether such effects are likely to occur it is necessary to quantify the nature and extent of stream-groundwater interactions. Of particular interest is the extent to which changes in river stage along Rocky Mountain streams affect water table levels in adjacent alluvial aquifers.

There has been a substantial effort in recent years to understand stream-groundwater interactions along small mountain streams due to the importance of the hyporheic zone for regulating stream temperature and nutrient fluxes (*cf.* Bencala et al., 1984; Castro and Hornberger, 1991; Harvey and Bencala, 1993; Wroblicky et al., 1994). However, only a handful of studies have focused on stream-groundwater interactions along higher-order mountain streams (Wondzell and Swanson, 1996), or on the effects of streamflow diversions on mountain wetlands. One such study showed that a proposed streamflow diversion along the Williams Fork in western Colorado would have little effect on the adjacent wetlands because most of the groundwater in the alluvial aquifer beneath the wetlands came from hillslope runoff and precipitation (Ruddy and Williams, 1991). In contrast, Rovey et al., (1986) suggested that the diversion of water from Cross Creek in the Holy Cross Wilderness would reduce back water effects resulting in a lowering of wetland water levels. A decline in riparian vegetation along Beaver Brook in Rocky Mountain National Park was attributed in part to partial dewatering of the stream caused by a flow diversion (Graf, 1997). Given these conflicting results and the increasing pressure on water resources there is a need to quantify stream-groundwater interactions in Rocky Mountain watersheds, so as to understand the impacts of existing and future streamflow diversions on the region's riparian areas and wetlands.

This paper reports on a three year study (1996-1998) of stream-groundwater interactions along a 1.4 km subalpine reach of the Colorado River in Rocky Mountain National Park (RMNP), Colorado (Figure 1). Streamflows along this section of the Colorado River are affected by a major water diversion, the Grand Ditch. This 24-kilometer diversion canal was constructed in the late 1800s to provide irrigation water for farms on the eastern side of the Continental Divide (McKnight, 1983). In the 1930s the Ditch was incorporated into RMNP, but the ditch owners maintained the right to divert water (McKnight, 1983). On average 29% of the annual discharge of the Colorado River at the USGS gauge below Baker Gulch (station no. 09010500) is diverted by the Grand Ditch (Woods, 2000). There is concern that reduced streamflow along the Colorado River has lowered the water table in the adjacent alluvial aquifer, and that this is having an adverse effect on riparian vegetation within RMNP.

The objectives of the study described here were to i) quantify the effect of the Grand Ditch on flow and stage in the Colorado River, ii) understand the extent of stream-groundwater interactions between the Colorado River and the adjacent alluvial aquifer, and hence, iii) determine whether reductions in Colorado River flow and stage result in lower water table levels in the adjacent riparian wetlands.

STUDY SITE

The study site comprised the 1.4-km Colorado River reach and the adjacent valley floor (Figure 2). Here the Colorado River flows almost directly south along a deep U-shaped valley known locally as the Kawuneeche Valley. The drainage area of the Colorado River at the top of the study reach is 94 km^2, of which 36 km^2 (38%) lies upstream from the Grand Ditch. Within the study reach the Colorado River is a gently meandering, pool-riffle channel that has a gradient of 0.2% to 0.8% and a mean width-to-depth ratio of 16 (Woods, 2000). The channel bed is comprised of gravel and small cobbles in the riffles with sand and gravel in the pools. There are no tributary inflows along the study reach.

The valley floor along the study reach is at approximately 2700 m elevation. The distance from the hillslopes to the Colorado River varies from less than 200 meters where a tributary stream alluvial fan extends part-way across the valley floor, to more than 500 meters in the widest section of the valley (Figure 2). The Colorado River floodplain lies approximately one meter above the stream bed, and varies in width from zero to more than 50 meters. The remainder of the valley floor is a terrace that is 0.7 to 1.2 m higher than the floodplain. There are numerous abandoned beaver ponds throughout the floodplain and terrace, but only a few active beaver colonies.

The floor of the Kawuneeche Valley is underlain by 15 to 120 meters of Holocene and upper Pleistocene alluvium (Braddock and Cole, 1990). The upper 1 –1.5 meters of this alluvium is typically silt loam and loamy sand. Much of the valley bottom is occupied by riparian shrublands dominated by several species of willow (*Salix* spp.). The higher parts of the terrace are dominated by grasslands and low shrubs.

Organic soils are found near groundwater seeps at the base of the hillslopes, and in abandoned beaver ponds. These organic soils typically consist of 30-50 cm of peat, underlain by up to a meter of either completely decomposed organic material or strongly gleyed silty clay. The vegetation in these areas is dominated by shrubby willows and herbaceous wetland plants such as *Carex* spp.

The eastern hillslope and the bedrock underlying the valley-fill alluvial aquifer are comprised of Pre-Cambrian metamorphics. The western hillslope is a lateral moraine deposited during the Pleistocene glaciation (Braddock and Cole, 1990). At the northwest corner of the study site this lateral moraine abuts the alluvial fan of Red Creek, which is a tributary of the Colorado River. The Red Creek alluvial fan is comprised of poorly sorted sediment ranging in size from clay to large cobbles and boulders. Groundwater seeps along the foot of the lateral moraine and around the edge of the alluvial fan support toeslope wetlands.

The nearest long-term weather station is Grand Lake 1NW, which lies 14 kilometers south of the study site (Figure 1). The mean annual precipitation at Grand Lake 1NW is 51.9 cm with a standard deviation of 9.8 cm. The period with lowest precipitation is typically from late May through mid-July. In late July and early August, monsoonal air flow causes high intensity, convective thunderstorms. Mean monthly temperatures at Grand Lake 1NW range from –7.9 °C in December to 16.1°C in July. Potential evapotranspiration (PET), calculated using the Thornthwaite method (Dunne and Leopold, 1978), ranges from 0 in the winter months to 7.7 cm in July. Mean monthly PET exceeds the mean monthly precipitation by 1-2 cm in June, July, August and September.

Annual runoff in the Colorado River headwaters is dominated by the spring snowmelt. On average, 81% of the annual runoff occurs in May, June and July. The mean annual instantaneous peak flow at the USGS gage on the Colorado River below Baker Gulch (USGS station no. 09010500) is 17.0 m^3/s, and occurs between late May and mid-June. Flow rapidly decreases during the early to mid-summer and baseflow conditions are usually reached by mid-August. Baseflows in mid- to late August are typically less than 1.5 m^3/s. Late summer monsoon storms can cause short-term increases in runoff, but the resulting peak flows are much smaller than the spring snowmelt peak.

METHODS

PRECIPITATION

Precipitation data were obtained from the Grand Lake 1NW climate station and from snow courses at Lake Irene and Phantom Valley (Figure 1). Grand Lake 1NW is at an elevation of 2658 m, and has a record of daily precipitation from 1948 to the present. The Phantom Valley snow course is near the Colorado River trailhead at 2752 m and has data from 1936 to the present. The Lake Irene snow course is adjacent to Trail Ridge Road at 3261 m and has data from 1938 to the present. Both of the snow courses have been operated as SNOTEL sites since the late 1970s, and have daily records of both precipitation and snow water equivalent (SWE). The data from Grand Lake 1NW, Phantom Valley and Lake Irene were used to evaluate the three study years in terms of the size of the winter snowpack and the amount of summer rainfall. For this purpose summer was defined as the period from 1 June through 31 August.

STREAMFLOW

Streamflow data were obtained for the USGS gage on the Colorado River below Baker Gulch and a gage operated by the Colorado Division of Water Resources on the Grand Ditch at La Poudre Pass (Figure 1). Both of these gages have daily flow records extending from 1954 until the present. Flow data from the Colorado River were used to develop peak and low flow frequency curves for the period of record, and these were compared to the peak and low flows during the study period.

Since the Grand Ditch was constructed in the late 1800s there were no flow data from the period prior to its construction. An estimate of the undiverted flows was obtained by summing the daily flows from the Colorado River gage and the DWR gage on the Grand Ditch. The summed daily flows were compared to the actual flows at the Colorado River gage to estimate the effect of the Ditch on streamflow.

The effect of the Grand Ditch on stream stage along the study reach was determined by installing and monitoring a temporary gaging station near the Timber Creek campground in early June 1996 (S2 on Figure 2). A Druck pressure transducer and Omnidata 900 data logger recorded stage at 15-minute intervals from early June through September in both 1996 and 1997. In 1998 stage data were recorded manually every 5 to 10 days.

The 15-minute stage data from 1996 and 1997 were converted to daily mean stage values. These daily mean values were then correlated with the corresponding daily mean flows at the USGS gage on the Colorado River using polynomial regression. By substituting the estimated undiverted flows at the USGS gage into this polynomial relationship we could calculate the undiverted stage values at Timber Creek. The difference between the observed stage and the estimated undiverted stage was assumed to represent the reduction in river stage due to the Grand Ditch.

A stage-discharge relationship for the Timber Creek gaging station was developed from six discharge measurements made between early July and late August 1997. Discharge measurements were made using the velocity-area method (Buchanan and Somers, 1965). Since it was not possible to safely measure discharge during high flows discharge at high flows was estimated by calculating the Manning roughness coefficient for the measured flows, and back-calculating the discharge using the measured channel geometry and Manning's equation (Dunne and Leopold, 1978).

STREAM - GROUNDWATER INTERACTIONS

Thirty-five monitoring wells were installed on the valley floor in June 1996 (Figure 2). Twenty-seven of these wells were located along three transects that extended across part or all of the Kawuneeche Valley. Transect A was the shortest transect as it extended across the narrowest part of the valley from the toe of the Red Creek fan to the river, and consisted of four wells (W1-W4). Transect B extended across a much wider part of the valley, from the western hillslope to the river, and consisted of ten wells (W5-W14). Transect C was the longest because it extended from the western hillslope across the Colorado River to the eastern hillslope. Transect C consisted of thirteen wells (W15-W27). The other eight wells (W28-W35) were located between the transects to help define the water table gradient between the transects and hence the direction of groundwater flow. Staff gages (S1-S3) were installed where each of the three transects reached the Colorado River.

All the monitoring wells were installed by hand auguring. A coarse gravel layer generally prevented the wells from being installed deeper than about 1.5 meters. Each well was made of 2.5-cm diameter PVC pipe that was slotted from the surface to the bottom of the well. The hole around each well was backfilled with native soil. The wells and staff gages were monitored every 5-10 days from early June through early September in 1996, 1997 and 1998. The elevations of the well casings, the ground surface at each well, and the staff gages were determined by surveying with a total station. All elevations were relative to a local benchmark. The saturated hydraulic conductivity (K) of the aquifer soils was estimated in ten wells by conducting rising head slug tests (Bouwer and Rice, 1976; Bouwer, 1989).

Two approaches were used to evaluate stream-groundwater interactions in the study area. The first approach used linear regression to determine the relationship between river stage and the water table level at each well. Due to the collinearity of hydrologic processes in the watershed, a high correlation between river stage and water levels was not necessarily an indication that the two were connected. However, if the slope of the regression was significant, and not significantly different from 1.0, then the well is likely to be hydrologically connected to the river.

The second approach used a two-dimensional numerical groundwater model to simulate the observed heads in the valley wells. The model was developed using the Visual MODFLOW software package from Waterloo Hydrogeologic Inc. (McDonald and Harbaugh, 1988). The model domain extended from the western to the eastern hillslope, and from transect A in the north to transect C in the south (Figure 2). A 20-meter horizontal grid with a total of 928 active grid cells was used. A well log from the east side of the Colorado River indicated that there were 23 m of alluvium, primarily sand and gravel (Welder, 1971). In the absence of any other stratigraphic information we used a single layer model with a thickness of 20 meters.

The Colorado River was modeled using the RIV routine in MODFLOW. The RIV routine calculates seepage to or from a stream within each cell based on the head difference between the stream and the aquifer. A streambed conductance parameter (C_{riv}) is used to account for the length and width of the stream channel within a cell as well as the bed thickness and hydraulic conductivity (Anderson and Woessner, 1992). Leakage across the stream boundary (Q_{riv}) is calculated using the equation:

$$Q_{riv} = C_{riv} (H_{riv} - h) \qquad (1)$$

where H_{riv} is the head in the stream and h is the head in the aquifer. Stage and river bottom elevation data for the Colorado River cells were based on data collected at the three staff gages. Stage values for river cells between the staff gages were interpolated.

The northern and southern boundaries of the model were constant head boundaries along the lines of transects A and C, respectively. The head values were based on the observed water table elevations along these transects. Fluxes across the constant-head boundaries represented the down-valley component of groundwater flow, which Larkin and Sharp (1982) termed 'underflow'.

Recharge boundaries were used to represent groundwater seeps at the base of the lateral moraine and around the toe of the Red Creek alluvial fan. The location of these seeps was based on field observations. The rest of the western boundary and the eastern boundary were zero-flow boundaries.

Model calibration was conducted using the well and stage data from mid-June to late August 1997. An initial transient calibration was conducted with no recharge from the hillslopes. The time-variable components of the model were the stage of the Colorado River and the head along each of the constant head boundaries. The hydraulic conductivity and the groundwater recharge at the foot of the hillslope were adjusted to improve the fit between the observed and calculated heads in monitoring wells W5-W14 (Transect B) and W28-W35.

Model fit was evaluated from time-series plots of the mean of the residuals (MR) and the mean of the absolute residuals (MAR) using the water level data for wells W5-W14 and W28-W35. MR is calculated as:

$$MR = \frac{\sum H_c - H_o}{18} \quad (2)$$

where H_c is the calculated head and H_o is the observed head in each well. MAR is calculated as:

$$MAR = \frac{\sum |H_c - H_o|}{18} \quad (3)$$

The calibrated transient model was validated using the measured water levels in the wells from 1996 and 1998. Where necessary, recharge rates at the hillslope were altered from the 1997 values in order to optimize the fit of the observed and calculated heads. Once a suitable model had been obtained to represent each year, we re-ran the simulations using the estimated undiverted stage values. The difference between the calculated water table elevations for the diverted and undiverted model simulations indicated the effect of the diversion on wetland water levels in each year.

RESULTS

PRECIPITATION

In 1996 the winter precipitation was well above average and this resulted in a large spring snowpack; the SWE values at Phantom Valley and Lake Irene on 1 April 1996 were 37.9 cm and 88.4 cm respectively, or 166% and 135% of their respective means (Table 1). The summer was exceptionally dry; summer precipitation at Grand Lake was only 8.3 cm or 56% of the mean (Table 2). Despite the dry summer, the annual precipitation at all three stations was about 110% of average because of the large winter snowfall (Table 2).

In 1997 winter precipitation was also well above average and produced a large spring snowpack. The SWE values at Phantom Valley and Lake Irene on 1 April 1997 were 26.9 cm and 74.5 cm respectively, or 117% and 114% of their respective means (Table 1). In contrast with 1996, summer precipitation was above average; at Grand Lake 1NW the summer rainfall total of 19.1 cm was 128% of the mean. The annual precipitation totals at Grand Lake and the two SNOTEL stations were all about 20% above the mean (Table 2).

The winter precipitation total for 1998 was below average and resulted in a relatively small spring snowpack. The SWE values at Phantom Valley and Lake Irene on 1 April 1998 were 19.8 cm and 52.3 cm respectively, which is only 87% and 80% of their respective means (Table 1). As in 1997, summer precipitation was well above average; at Grand Lake the summer total was 139% of the mean. Annual precipitation in 1998 was close to the mean at all three monitoring stations because the small winter total was offset by the subsequent wet summer (Table 2).

STREAMFLOW

In 1996 the instantaneous annual peak flow of the Colorado River at the USGS gage below Baker Gulch was 18.9 m^3/s and occurred in early June (Figure 3a). This is close to the mean annual peak flow and has an estimated recurrence interval of 2.4 years. After a brief spike in late June the flow of the Colorado River declined rapidly in July. The Grand Ditch began diverting water in mid-May and continued operating until mid-

September (Figure 3a). During early August 1996 the Grand Ditch was intercepting more than 60% of the total daily runoff. The 3-day summer low flow for the Colorado River in 1996 was only 0.48 m^3/s, which has an estimated recurrence interval of 10 years. This exceptionally low flow was caused by the lack of summer rainfall and the diversion of flow by the Grand Ditch.

In 1997 the annual peak flow at the USGS gage was 22.3 m^3/s and occurred in mid-June. This was the highest peak flow recorded during the study period and has an estimated recurrence interval of 5.1 years. The recession limb of the snowmelt hydrograph was exceptionally steep in 1997, and flows dropped below 5 m^3/s by early July (Figure 3b). As in 1996 the Grand Ditch began operating in mid May, and by the first week of August it was intercepting over 60% of the total daily runoff. However, in contrast with most other years, several of the headgates on the Ditch were reopened over a short period in mid-August and this resulted in a sharp increase in the flow of the Colorado River (Figure 3b). The Ditch also ceased operating by the end of August, so the 1997 3-day low flow was 1.48 m^3/s, which is much higher than average.

The peak flow in 1998 was 12.0 m^3/s, which is only 70% of the mean. A second, smaller peak flow occurred at the beginning of July, after which flows gradually declined (Figure 3c). As in 1996 the Ditch operated from mid-May until late September. During most of August the Ditch was intercepting more than 60% of the mean daily flows. Low flows in 1998 were lower than average; the 3-day low flow of 0.66 m^3/s has a recurrence interval of slightly less than 5 years.

The highest stage value measured at staff gage S2 during the study period was 0.92 m on 19 June 1997, and the lowest stage was 0.36 m on 17 August 1996. This indicates a total range in stage of 0.56 m.

The mean daily stage at the temporary gaging station near the Timber Creek campground (H_{TC}) was related to mean daily discharge (Q) at the USGS gaging station below Baker Gulch by the relationship:

$$H_{TC} = 0.4233Q^{0.2355} \; (r^2 = 0.97) \qquad (4)$$

This relationship provided a reasonable fit to the observed values except in late June 1997 when the river stage dropped very rapidly over a period of 4-5 days. During this period equation 4 substantially overpredicted the actual river stage, and this was probably due to the lagged response at the USGS gage (Figure 4).

From 1996 to 1998 the calculated decrease in stage due to the Grand Ditch ranged from 0 to nearly 20 cm. In 1996 the difference in the peak stage in early June was only about 5 cm. The greatest decrease was in mid-July, when the ditch caused a 10-15 cm decline in stage relative to the estimated undiverted stage. The effect of the diversion then gradually decreased to zero by mid- to late September (Figure 4a).

In 1997 the ditch had no effect on stage until mid-June. The difference between the observed stage and the predicted stage without the diversion was 15-20 cm throughout July and early August. After the ditch stopped operating in mid-August, the river stage at Timber Creek campground immediately rose by 18 cm, suggesting that the modeled differences were close to the actual drawdown (Figure 4b).

In 1998 the reduction in peak stage was about 10 cm (Figure 4c). In June and July the reduction in stage was almost identical to 1996, as the drawdown was about 10-15 cm. In August and early September the difference in stage gradually decreased to zero.

These results indicate that the reduction in peak stage ranges from nearly zero to about 20 cm in most years. In terms of the percentage reduction in peak stage, the greatest effect occurs in years with small peak flows because the amount of water diverted is a larger proportion of the total runoff. During the critical months of July and August, the effect on stage tends to be about the same from year to year and is in the range of 10-20 cm.

STREAM – GROUNDWATER INTERACTIONS

In each year the highest water levels in each of the groundwater monitoring wells occurred in the early summer. The timing of these peaks coincided with the peak stage of the Colorado River. Figure 5 shows groundwater levels and river stage along transect B in 1996, 1997 and 1998, and these data illustrate the general trends in most of the wells.

In 1996 water levels in all of the wells gradually declined throughout June, July and August. The lowest water table levels occurred in mid- to late August and coincided with the base flow period in the Colorado River (Figure 5a). These were also the lowest water levels measured at any time during the study.

In 1997 water levels also declined throughout June, July and the first week of August. However, due to a combination of high rainfall and the rise in river stage along the Colorado River following the end of the diversion, water levels rose slightly in mid-

August, and the seasonal minimum water levels in most wells were not as low as in 1996 (Figure 5b).

In 1998 peak water levels were slightly lower than in 1996 and 1997, and this was presumably due to the smaller snowpack. As in 1997, water levels dropped gradually during June and early July, but then increased slightly in late July in response to the onset of late summer rainfall (Figure 5c).

Statistical analysis of water table levels and river stage

Since both water table levels and river stage tended to decline throughout the summer the resulting linear regressions were statistically significant in almost all cases (Table 4). However, there was considerable variation in the correlation coefficients and regression slopes among the different wells, indicating spatial variability in the extent to which water table levels were connected to the Colorado River. Since the wells in transect B encompass the range of results from all wells, the transect B wells are discussed in more detail. Variability between the transects is then discussed using the data from transects A and C.

Well W14 is the nearest well to the river on transect B; it lies approximately 10 m from the Colorado River and 15 m downstream from staff gage S2. The regression analysis indicated that the water table level was closely related to river stage, as the slope of the regression line was 1.00 and the r^2 was 0.76 (Table 4). While the latter value is comparable to three of the other wells on the transect, a plot of the data shows a strong linear relationship except for two points (Figure 6a). These two points are due to the slow response of the water table to the rapid decline in river stage that occurred in late June

1997 (Figure 5b). Although the correlation coefficient was similar to several other wells on the transect, the slope of the regression line for W14 was the closest to 1.0 (Figure 6a and Table 4).

The next well along transect B is W13, which lies approximately 80 m from the river on the east side of an oxbow. Water levels in this well were close to the river stage at high flows, but tended to drop faster than the river for much of the summer (Figure 6b). Although the r^2 was about the same as for W14, the slope of the regression was significantly greater than 1.0 (Table 4). As in the case of W14, there were several points above the regression due to the delayed response in W13 following a sharp drop in river stage in late-June of 1997.

Well W12 is 140 m from the Colorado River and about 0.4 m higher than well W14. The water level in W12 was 40-50 cm above the river in the early summer of all three years, and water levels in this well declined more rapidly than the river (Figure 6c). Although the r^2 was slightly higher than for W13 and W14, this is largely due to the absence of any outliers. Because the slope of the regression was significantly larger than 1.0, and water levels in W14 were always above the river stage, river stage was not the primary control on water levels in W12. The fact that the water level in W12 was higher than the river in early summer suggests that hillslope runoff, or the down-valley movement of groundwater, were the primary controls on water levels in this well.

One of the most surprising results from transect B was that the linear regression for well W11, which is 200 m from the Colorado River, indicated a closer connection to river stage than W12 or W13. The slope of the regression was not significantly different from 1.0, and the r^2 was the second highest for any well on the transect. However, the water level in W11 was always at least 70 cm above the river stage at S2 (Figure 6d). This anomaly could be due to the collinearity between the recession of the Colorado River and the overall decline in water table levels due to aquifer depletion during the summer. It could also indicate that there is a downstream component of groundwater flow that causes water levels in W11 to respond to stage changes further upstream.

The next two wells along transect B are W9 and W10, and these are around the edge of a large beaver pond. Although this pond was not occupied by beavers during the study period, it was flooded in the early summer by a combination of snowmelt and inflow from a small perennial stream. Water levels in W9 and W10 had the lowest correlation with river stage of any wells along transect B, as the water levels in both wells tended to drop much faster than the river at low water levels (Figures 6e and 6f). Thus, although the slope of the regression was close to 1.0 for both wells, this does not equate to a close hydrologic connection between these two wells and the Colorado River. The sharp drop in water levels in the late summer occurred after the adjacent pond went dry, suggesting that the pond is the primary control on water levels in these two wells.

The results of the monitoring at transect B showed that, in general, the effect of the Colorado River on water table levels decreased with distance from the river, while the importance of factors such as hillslope runoff, the down-valley flow of groundwater, and water levels in ponds on the valley floor increased. However, the results from W11 suggest that river stage can still affect groundwater levels up to 200 m from the river.

The results of the statistical analysis of water level data from transect C were generally consistent with transect B, and support the concept of a transition from river-dominated groundwater to hillslope-dominated groundwater with increasing distance from the river. Wells W20 and W21 both lie within 10 m of the Colorado River. The r^2 values for these two wells were only 0.54 and 0.56 respectively, but this was largely due to the low sample size caused by the fact that both wells went dry in the mid summer. The regression slopes for both wells were close to 1.0, and water levels increased in response to the stage increase in August 1997, indicating that these two wells are connected to the Colorado River. Water levels in the middle of the transect on both sides of the river dropped faster than the river, so the slope of the regressions were greater than 1.0. However, water levels in these wells increased in response to stage changes in late summer, such as in August 1997. Finally, water levels in the wells furthest from the river, such as W15 and W16, showed no evidence of being related to river stage. Well W15, for example, had a regression slope of 0.32 and an r^2 value of just 0.15 (Table 4).

The results from transect A were different in several respects from the other two transects. The two wells nearest the Colorado River are W3 and W4, which lie 10 m and 60 m from the Colorado River, respectively. When data from wells W3 and W4 were analyzed, the regression equations were more like those for the middle parts of the other two transects than for wells near the river (Table 4). In both cases the regression slopes were significantly greater than 1 because the water levels were much higher than the river in the early summer and then dropped relatively quickly. The implication is that the river stage has little effect on water levels even in wells as close as 10 m from the river bank.

The other two wells on transect C were W1 and W2, which lie 150 m and 200 m from the river, respectively. When water level data from W1 and W2 were statistically compared to the river stage, the r^2 values were relatively low (Table 4). However the regression slopes were both approximately equal to 1.0, indicating a close connection to the Colorado River. This seems unlikely given the fact that both of the wells nearer the Colorado River are unconnected to river stage. As with W11 on Transect B, this anomaly may be due to the collinearity of hydrologic processes rather than a direct connection to the Colorado River.

The results from transect C can be explained by the varying effect of valley geomorphology on transect groundwater levels. In broad, unconfined valley sections like at transects B and C, there is a gradual transition from hillslope-dominated to stream-dominated as one gets closer to the river. However, transect A is in a much more confined section of the valley, so water levels were controlled by hillslope runoff throughout the summer. Hillslope processes appeared to be dominant even in wells as little as 10 m from the river.

Groundwater model calibration

The initial calibration of the numerical model to the 1997 water table levels used a hydraulic conductivity of 10^{-6} m/s for the entire alluvial aquifer. This value was chosen because the arithmetic mean of the ten falling head tests was 2.8 x 10^{-6} m/s and the range was from 2.5 x 10^{-8} cm/s in W14 to 6.8 x 10^{-6} cm/s in W20. These initial calibration efforts also did not have any groundwater discharge at the toe of the lateral moraine.

The initial calibration runs yielded water table declines in wells near the Colorado River that were substantially less than the observed values. In contrast, the water table declines in the wells near the hillslope were substantially greater than the observed values. The mean of the residuals (MR) for this initial model run ranged from –0.72 m to -0.82 m, with a mean of –0.78 m. Since the MR was always negative the mean of the absolute residuals (MAR) was the absolute value of the MR. An improved fit between the observed and calculated heads was obtained by increasing the hydraulic conductivity in the floodplain and terrace to 2-5 x 10^{-3} m/s. The resulting MR ranged from –0.44 m to –0.83 m, with a mean of -0.59 m. Again, the MAR was the absolute value of the MR. While hydraulic conductivities in the range 2-5 x 10^{-3} m/s are clearly not representative of the silt and sand-dominated sediments in the upper 1 – 1.5 meters of the soil profile, they are consistent with the likely hydraulic conductivity of the underlying gravel horizon (Freeze and Cherry, 1978). This change suggests that the response of the alluvial aquifer to seasonal changes in river stage and hillslope recharge is largely controlled by the underlying gravel rather than the fine-grained sediments in the upper 1 – 1.5 meter depth interval.

The fit between the observed and calculated heads was further improved by introducing groundwater recharge fluxes at several points along the hillslope. The resulting MR for the calibrated 1997 transient simulation ranged from zero to –0.11 m with a mean of –0.05 m, and the MAR ranged from 0.22 to 0.30 m with a mean of 0.27 m (Figure 7). Since the total range in heads within the model domain was approximately 9 m, these MR and MAR values indicate a reasonably good fit between the observed and calculated water table levels.

The initial model runs for the 1996 and 1998 transient simulations yielded similar MR and MAR values to those for 1997. The exception was in the late summer of 1996, when the model errors increased substantially because the calculated water table declines at the hillslope were much less than the observed values. However, when the recharge fluxes at the hillslope for this period were decreased by 12 to 18%, both the MR and

MAR were brought back within the range observed in the other two years (Figure 7). The MR for the calibrated 1996 transient simulation ranged from –0.06 to +0.01, with a mean of 0.00 m, and the MAR ranged from 0.26 m to 0.29 m with a mean of 0.28 m. The MR for the calibrated 1998 transient simulation was similar to 1996, ranging from –0.05 m to 0.09 m with a mean of 0.02 m. The MAR for the 1998 simulation was also similar to 1996, ranging from 0.25 m to 0.30 m with a mean of 0.28 m.

Model simulations of groundwater flow and stream-groundwater interactions

Throughout the study period the predominant direction of groundwater flow in the alluvial aquifer was down-valley. Figure 8 shows the predicted elevation of the water table and the groundwater flow velocity vectors for 5 July 1996, approximately two weeks after the annual peak flow, and these are reasonably typical of conditions throughout the study.

The model simulations indicated that the down-valley component of groundwater flow at the upstream end of the study site ranged from a maximum of 0.28 m^3/s (24000 m^3/day) in late June 1997 to a low of 0.2 m^3/s (17000 m^3/day) in August 1996 (Figure 9a). Since the calculated streamflows at these times were 7.1 and 0.2 m^3/s, respectively, this means that subsurface flow accounts for less than 4% of the total runoff from the watershed during peak flows, but as much as 50% during low flows.

Hillslope groundwater discharge into the alluvial aquifer was typically less than 12% of the down-valley component of flow, and remained relatively constant from year to year (Figure 9b). In the early to mid-summer of each year the total flux from the hillslope was less than 0.02 m^3/s (2000 m^3/day). More than 90% of this flux came from around the margins of the Red Creek alluvial fan. This is consistent with the distribution of slope wetlands at the western margin of the valley, and peat deposits in wetlands around the alluvial fan. The remainder of the hillslope groundwater came from an area near the western end of transect C, where there is a slope wetland at the base of the hillslope.

The calibrated model indicated that there was a large and dynamic exchange of water between the alluvial aquifer and the Colorado River. While some reaches lost water to the aquifer, other reaches were gaining. Leakage from the Colorado River into the alluvial aquifer ranged from 0.08 to 0.22 m^3/s (7200 to 19000 m^3/day). The lowest leakage rate coincided with peak flows in June 1997, when groundwater levels along most of the study reach were slightly higher than the stage of the Colorado River (Figure 10a). Leakage rates increased throughout the summer because groundwater levels tended to drop faster than the river stage. Despite the large flux of water from the river to the aquifer most of the subsurface flow of stream water occurred within 20 to 50 meters of the Colorado River. This is most clearly illustrated by the flow vectors shown in Figure 8.

Groundwater discharge to the river along the study reach ranged from 0.15 to 0.27 m^3/s (13000 to 23000 m^3/day), (Figure 10b). The highest discharge rates occurred during the peak flow period in June 1997. Groundwater discharge to the river increased by 0.10 m^3/s after the end of the diversion in August 1997. Approximately 60% of this increase was due to a corresponding increase in stream leakage along the study reach, and the remainder was due to an increase in the down-valley flux at the upstream end of the study site.

During most of the three year study period there was a net gain in flow along the study reach (Figure 10c). For most of the study period this gain ranged from nearly zero to just under 0.1 m^3/s. The biggest increase in flow along the study reach was 0.2 m^3/s in June 1997. The only period when there was a net loss of flow along the reach was in the late summer of 1996, when groundwater levels were exceptionally low due to the dry summer. During this period the net loss in flow ranged from 0.02 to 0.04 m^3/s.

Model predictions of the effect of the Grand Ditch on water table levels

The decline in groundwater levels due to the Grand Ditch, based on a comparison between model simulations using the observed stage and the estimated undiverted stage, varied seasonally and between years, and also with distance from the river. In general, the average water table decline in the wells increased during June and early July, reached a peak in mid-July and then declined throughout late July and August (Figure 11).

In 1996, the average water table decline in the early summer was approximately 0.06 m. The average water table decline increased throughout June and early July, reaching a peak of 0.08 m by mid-July. It then declined rapidly during the rest of July and August. By the end of August the average water table decline was less than 0.01 m.

The seasonal trend in 1997 was similar to 1996. However the early summer water table decline was just 0.03 m, and the difference was presumably due to the larger amount of snowmelt runoff in 1997, which diminished the effect of the diversion. The average water table decline in mid-July was almost the same as in 1996. The smallest water table declines during the study period occurred in late August 1997 because the Grand Ditch ceased operating earlier than usual. The 1 cm decline in water levels indicated during this period on Figure 11 is due to a lagged response to the end of the diversion in wells further from the river.

In 1998 the average water table decline in the early to mid summer was larger than in either 1996 or 1997, indicating that the diversion has a greater impact on June and July water levels in years with a small snowpack. However by early August the decline in water levels was similar to 1996 and 1997, indicating that the effect on water levels at this point in the summer varies very little from year to year.

The magnitude of the decline in water table levels decreased with distance from the river, and the results from wells W14, W11 and W9 illustrate this trend. In well W14, which is just 20 m from the Colorado River along transect B, the maximum water table decline was 0.11 m in 1997 and 0.12 m in 1996 and 1998 (Figure 12a). The maximum water table decline in well W11, which is 200 m from the river along transect B, ranged from 0.09 m in 1996 and 1997 to 0.10 m in 1998 (Figure 12b). The maximum water table decline in well W9, which lies approximately 400 m from the river on Transect B, was even smaller ranging from 0.06 m in 1996 to 0.09 m in 1998 (Figure 12c).

DISCUSSION

Analysis of stream – groundwater interactions dates back to the pioneering work of Boussinesq in the late 19th century (Winter, 1995). Subsequent stream-groundwater interaction studies have employed methods ranging from semi-quantitative comparisons between groundwater and streamflow hydrographs (*cf.* Doty et al., 1984) to complex numerical groundwater flow models (*cf.* Watts and Lindner Lunsford, 1982; Wolf and Helgesen, 1993; Wroblicky et al., 1998). Several studies have used relatively simple data analysis and conceptual models to then guide more rigorous, process-based methods (*cf.* Sophocleus, 1991; Vekerdy and Meijerink, 1998), and we followed a similar strategy.

LINEAR REGRESSION ANALYSES

Linear regression is often used to test the strength of the relationship between river stage and water table levels, and to develop predictive models (Adamowski and Feluch, 1991). The results of our analysis showed that wells closer to the river tended to be more highly correlated with the river stage, but there was considerable spatial variability in the strength of this relationship. Bell and Johnson (1974) also showed that the coefficient of determination between floodplain water levels and the river stage decreased with increasing distance from the river.

The observed variability in the relationship between groundwater levels and river stage along each of the transects was likely due to variations in aquifer geology, proximity to surface water bodies and valley geomorphology. Several studies have shown that spatial variability in aquifer geology is the main cause of variations in the response of floodplain wells to river stage changes. In the Big Bend aquifer in Kansas, wells screened in channel fill deposits responded more rapidly to stage changes than wells screened in overbank deposits. The difference was due to the contrast in hydraulic conductivity between the two sediment types (Sophocleus, 1991). The lag time corresponding to the maximum correlation between hydrographs of groundwater observation wells and the stage of the river Danube in Hungary was longer in unconfined parts of the aquifer than in the semi-confined parts (Vekerdy and Meijerink, 1998). Much of the observed variability in the relationship between groundwater levels and the stage of the Colorado River at our study site is also probably due to variability in the geology of the alluvial aquifer.

Wells located in close proximity to beaver ponds were generally more responsive to water level fluctuations in the ponds than to river stage changes. Although surface water bodies such as lakes and ponds are generally considered to be located in groundwater discharge areas, they can also be sources of aquifer recharge (Winter 1999). This may well be the case for the beaver ponds in the Kawuneeche Valley, which trap surface water runoff from the hillslopes which then percolates to the water table. Seepage from a beaver pond was an important source of aquifer recharge adjacent to Bridge Creek in central Oregon (Lowry and Beschta, 1994).

In our study the wells along transect A were generally less well connected to the river than the wells along transects B and C. The valley floor at transect A is constricted by the Red Creek alluvial fan, and this fan is a major source of groundwater discharge (Woods, 2000). This means that hillslope discharge is probably the dominant control on groundwater levels along the entire length of transect A. In contrast the Colorado River appeared to be an important control on water levels along portions of transects B and C. Differences in valley confinement also had a major influence on stream-groundwater interactions along a stream in the Sierra Nevada (Harris, 1988).

GROUNDWATER FLOW MODELING

While regression analysis is a convenient test of the relationship between groundwater levels and river stage, a high correlation does not prove cause-and-effect. This is particularly true in high elevation watersheds in the Rocky Mountains, where streamflow, hillslope runoff and vertical aquifer recharge rates are driven by the combination of spring snowmelt and summer water deficits. We therefore used a numerical model to further evaluate the linkage between the alluvial aquifer and the Colorado River.

The development of PC-based numerical models such as MODFLOW (McDonald and Harbaugh, 1988) has facilitated more rigorous analyses of stream-groundwater interactions in geologically complex environments. A two-dimensional finite difference model helped to explain the spatial variability in the response of water levels in the Great Bend alluvial aquifer in Kansas to river stage changes (Sophocleus, 1991). A steady-state numerical model was used to predict the effect of deepening the Arkansas River on water table levels in an alluvial aquifer near La Junta, Colorado (Watts and Lindner-Lunsford, 1992). Wroblicky et al. (1998) used MODFLOW to compare the lateral extent of the hyporheic zones of two northern New Mexico streams.

The calibrated MODFLOW model of our study area helped us to understand the relative importance of different aquifer recharge sources, estimate the exchange between the aquifer and the Colorado River, and predict the effect of the Grand Ditch on water levels in the alluvial aquifer. Although we had three years of data from 35 monitoring wells our calibrated model is still an abstract representation of reality, and the results must be considered in the light of errors and limitations in the model formulation, calibration and validation.

The heads predicted by the calibrated model agreed well with the observed water levels in all three years of the study. However, the calculated subsurface fluxes are subject to considerable error because of uncertainty in defining the hydraulic conductivity of the aquifer and the aquifer thickness. The calibrated model simulations indicated that the alluvial aquifer has a hydraulic conductivity approximately 3 orders of magnitude larger than those indicated by the falling head tests in the monitoring wells. We assumed that this was because most of the aquifer consists of gravelly alluvium, rather than the silty and sandy material in the uppermost 1 – 1.5 meters. However, a lack of deep wells prevented us from verifying whether this is actually the case.

The lack of deep wells also prevented us from confirming the aquifer thickness. The downstream component of groundwater flow is particularly sensitive to variations in the aquifer thickness. We estimated the aquifer thickness to be 20 m based on the data from a single well boring drilled near the Timber Creek campground. However wells drilled in other parts of the Kawuneeche Valley have penetrated up to 122 m of alluvium (Braddock and Cole, 1990) so the actual aquifer thickness may be substantially greater than 20 meters. If this is the case then the downstream groundwater fluxes indicated by the model simulations would be an underestimate of the true values.

The best means of validating the calculated fluxes is to compare them to a known flux within the system. In our case the only known flux is a 0.91 m^3/s increase in flow between the temporary gage at Timber Creek campground and the USGS gage on 22 August 1997. Since the difference in drainage area between these two stations is 44.4 km^2, the average increase in flow was 0.02 $m^3s^{-1}km^{-2}$. The difference in drainage area between the upstream and downstream ends of the study reach is 4.8 km^2. If runoff is proportional to drainage area, we would expect a net increase in flow of about 0.1 m^3/s along the reach. The calculated increase in flow along the study reach during this period was 0.01 m^3/s, indicating that the calculated fluxes between the Colorado River and the alluvial aquifer may be as much as an order of magnitude less than the actual values.

One of the most interesting results of our study is the fact that as much as 50% of the runoff can occur by subsurface flow. Larkin and Sharp (1992) provide several examples of alluvial aquifers where the dominant component of groundwater flow was parallel to the stream. They referred to the down-valley component of groundwater flow as underflow to distinguish it from the flow perpendicular to the stream, which they termed baseflow. The Colorado River is similar to the type of stream that Larkin and Sharp (1992) identified as most likely to be underflow dominated. They found that underflow dominated aquifers typically occur adjacent to mixed-load or bedload-dominated streams that have slopes greater than 0.0008, sinuosity of less than 1.3, width-to-depth ratios greater than 60 and penetration of less than 20%. Although the Colorado River has a width-to-depth ratio of less than 20, it does meet the other criteria defined by Larkin and Sharp (1992) for an underflow dominated stream-aquifer system.

The subsurface water moving parallel to the Colorado River must come from a combination of hillslope runoff, vertical recharge from infiltrating rain and snowmelt, and leakage from the Colorado River. Our study site lies approximately 4 km downstream from a highly confined section of the Kawuneeche Valley. Presumably all of the downstream flux along this confined section is contained within the river, so all of the subsurface flow at our study site must enter the aquifer along the intervening 4 km section of the valley. If we assume that the lateral inflow rate along our study reach of 0.014 $m^3s^{-1}km^{-1}$ is representative, then hillslope runoff provides about 0.16 m^3/s, or between 41% and 56%, of the observed downstream fluxes at the upstream end of the study site. If we assume a mean valley width of 300 meters along the 4 km reach, and annual precipitation of 0.5 m, then precipitation provides an additional 0.02 m^3/s of this downstream flux. However this still means that between 0.08 and 0.15 m^3/s, or between 38% and 54% of the downstream flux, must be from stream leakage along the 4 km reach. This is similar to what Stanford and Ward (1988) found on the Flathead River in Montana, where stream leakage was the primary source of aquifer recharge where the river went from a confined to an unconfined reach.

EFFECT OF THE GRAND DITCH ON WATER TABLE LEVELS

A key objective of our study was to determine if the reductions in river stage caused by the Grand Ditch have lowered water levels in the riparian area along the Colorado River. Since many riparian plants are either facultative or obligate phreatophytes - meaning that they use groundwater for some or all of their water supply – lowering of the water table may cause drought-induced mortality of riparian trees and shrubs (Kondolf et al. 1987; Smith et al., 1991; Tyree et al. 1994). Less severe water table drawdowns may cause a shift in species composition in favor of species adapted to a deeper water table. The extent to which direct mortality or a change in species composition is likely to occur depends on whether riparian plants use soil water or groundwater as their primary water source, the relative importance of the river in controlling the water table, and the magnitude of the decrease in the water table due to a decrease in river stage.

The dominant riparian shrub in the Colorado River headwaters is willow (*Salix* spp.).Isotopic analyses indicated that willows growing on the east side of Rocky

Mountain National Park obtained 80% of their water supply from groundwater (Alstad et al., 1999). The roots of mature willows in cut banks along the Colorado River extend well below the present water table. Since the top of these banks is up to 1.5 meters above bankfull and much of the valley floor is at a similar elevation with respect to the Colorado River, it is likely that many of the mature willows in the study area also use groundwater for at least part of their water supply.

We found that while the discharge of the Colorado River has been reduced by as much as 60% during the summer, the maximum decline in stage due to the Grand Ditch is only 0.20 m, and the maximum predicted decline in the water table is just 0.12 m. A water table decrease of 0.12 m or less is unlikely to reduce the availability of water for the deeply-rooted mature willows that occupy much of the valley floor. Field observations indicate no evidence of drought-induced willow mortality in the Kawuneeche Valley. However, many herbaceous species in the understory of the riparian zone have relatively shallow roots, and these may be affected by even a small drop in the water table. Thus while trees and shrubs may show little or no change in species composition, greater changes may have occurred in the herbaceous understory.

CONCLUSIONS

Our linear regression analyses of the relationship between river stage and water table levels in 27 wells indicated that the effect of the Colorado River on water table levels decreased with distance from the river. However, hillslope runoff was more important than the Colorado River for controlling water table levels in confined valley sections. The strength of the relationship between river stage and water table levels varied depending on the proximity of beaver ponds and oxbows, indicating that these may be sources of groundwater recharge.

Our calibrated numerical groundwater model indicated that the predominant direction of groundwater flow was down-valley. Consequently, between 4% and 50% of the total runoff occurred by subsurface flow in the alluvial aquifer. Hillslope groundwater discharge was typically less than 12% of the down-valley component of flow. There was a large and dynamic exchange of water between the alluvial aquifer and the Colorado River, with leakage into the alluvial aquifer ranging from 0.08 to 0.22 m^3/s, and discharge to the river ranging from 0.15 to 0.27 m^3/s. The net flux ranged from a gain of 0.2 m^3/s in June 1997 to a loss of 0.04 m^3/s in August 1996.

The water table declines due to the diversion ranged from 0.01 m to 0.12 m. The maximum declines were in mid-July, in wells near the Colorado River. Smaller declines were predicted earlier and later in the year, and in wells further from the river. Declines of less than 0.12 m are unlikely to adversely affect mature, deeply rooted riparian trees and shrubs. However, changes may have occurred in the species composition of the shallow-rooted herbaceous understory.

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Table 1. Snow water equivalent (SWE) values on 1 April at Phantom Valley and Lake Irene SNOTEL sites in 1996, 1997 and 1998.

	Phantom Valley		Lake Irene	
Year	cm	percent of mean	cm	percent of mean
1996	37.9	166	88.4	135
1997	26.9	117	74.5	114
1998	19.8	87	52.3	80
Mean (SD)	22.9 (6.4)		65.6 (16.1)	

Table 2. Annual, winter and summer precipitation in centimeters at Grand Lake, Phantom Valley and Lake Irene in 1996, 1997 and 1998 compared to mean values. GL = Grand Lake, PV = Phantom Valley, LI = Lake Irene. Mean values for Grand Lake are based on period of record, with standard deviations (SD) in parentheses. Mean values for Phantom Valley and Lake Irene are from USDA (1998), and are based on the period 1961-1990.

	Annual			Winter			Summer		
	GL	PV	LI	GL	PV	LI	GL	PV	LI
1996	56.7	75.9	102.6	36.1	56.7	79.6	8.3	12.2	13.2
1997	65.5	80.0	108.0	46.3	55.9	83.3	19.1	16.3	16.5
1998	51.8	58.2	88.1	24.6	36.3	61.2	20.1	19.8	23.6
Mean	51.9	65.6	90.8	32.6	48.3	70.4	14.9	13.2	15.5
(SD)	(9.8)			(7.0)			(5.7)		

Table 3. Total annual runoff and proportion of the total runoff that was diverted by the Grand Ditch in 1996, 1997 and 1998. Total runoff is the sum of flows in the Colorado River below Baker Gulch (USGS gage no.09010500) and the Grand Ditch at La Poudre Pass. Mean values are from 1954-1998, and the standard deviation (SD) is in parentheses.

	Total runoff (m^3)	Amount diverted (m^3)	Percentage of runoff diverted				
			Total	May	June	July	August
1996	1.0×10^8	2.9×10^7	27	4.0	33.5	56.4	55.4
1997	1.2×10^8	2.2×10^7	19	2.5	18.1	54.1	21.8
1998	7.7×10^7	2.6×10^7	34	16.3	40.0	55.7	47.8
Mean	7.9×10^7	2.2×10^7	29	10	32	51	48
SD	2.0×10^7	4.9×10^6	8	11	16	10	9

Table 4. Regression analyses of water table elevations (H_w) versus river stage elevation (H_r) for 23 wells along transects A, B and C. p (H_0: $B_0 = 0$) is the p-value for the null hypothesis that the regression coefficient (B_0) is equal to 0. p (H_0:$B_1 = 1$) is the p-value for the null hypothesis that the slope of the regression (B_1) is equal to 1. p-values significant at $p \leq 0.05$ are shown in bold type.

Well No.	n	Regression equation	r^2	p (H_0: $B_0 = 0$)	p (H_0:$B_1 = 1$)
Transect A					
W1	34	$H_w = 0.83\ H_r + 2.82$	0.59	**<0.001**	0.165
W2	37	$H_w = 1.01\ H_r + 0.61$	0.41	**<0.001**	0.966
W3	37	$H_w = 2.31\ H_r - 9.04$	0.79	**<0.001**	**<0.001**
W4	37	$H_w = 1.79\ H_r - 5.44$	0.75	**<0.001**	**<0.001**
Transect B					
W9	20	$H_w = 1.08\ H_r + 0.75$	0.54	**<0.001**	0.671
W10	30	$H_w = 1.06\ H_r + 0.88$	0.45	<0.001	0.824
W11	39	$H_w = 1.10\ H_r + 0.44$	0.79	**<0.001**	0.277
W12	39	$H_w = 1.68\ H_r - 1.56$	0.80	**<0.001**	**<0.001**
W13	39	$H_w = 1.69\ H_r - 2.05$	0.75	**<0.001**	**<0.001**
W14	39	$H_w = 1.00\ H_r - 0.09$	0.76	**<0.001**	0.982
Transect C					
W15	36	$H_w = 0.32\ H_r + 0.36$	0.15	**0.012**	**<0.001**
W16	35	$H_w = 0.86\ H_r + 0.38$	0.33	**<0.001**	0.508
W17	37	$H_w = 1.27\ H_r + 0.14$	0.66	**<0.001**	0.073
W18	37	$H_w = 1.52\ H_r + 0.33$	0.49	**<0.001**	**0.044**
W19	37	$H_w = 1.36\ H_r + 0.20$	0.73	**<0.001**	**0.014**
W20	23	$H_w = 0.93\ H_r - 0.08$	0.54	**<0.001**	0.616
W21	23	$H_w = 0.74\ H_r - 0.17$	0.56	**<0.001**	0.079
W22	37	$H_w = 0.94\ H_r + 0.20$	0.62	**<0.001**	0.651
W23	37	$H_w = 1.86\ H_r + 0.89$	0.69	**<0.001**	**<0.001**
W24	37	$H_w = 1.04\ H_r + 0.21$	0.56	**<0.001**	0.782
W25	37	$H_w = 0.54\ H_r + 0.52$	0.61	**<0.001**	**<0.001**
W26	35	$H_w = 0.53\ H_r + 0.54$	0.25	**0.001**	**0.004**
W27	37	$H_w = 0.40\ H_r + 0.61$	0.31	**<0.001**	**<0.001**

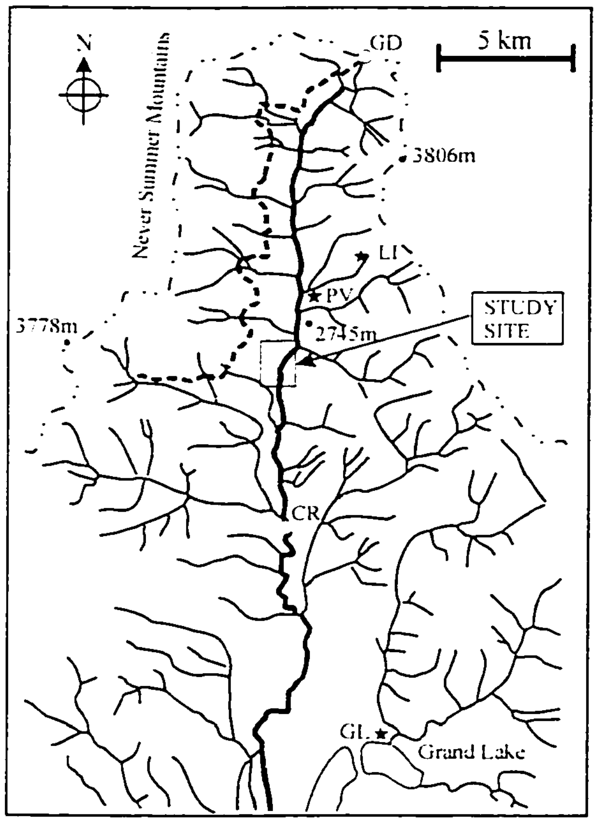

Figure 1. Map of Colorado River headwaters near Grand Lake, Colorado, showing location of climate monitoring stations (solid stars) and stream gaging stations (open circles). The thick solid line is the main stem of the Colorado River, and the thinner solid lines are tributary streams. The dashed line is the Grand Ditch. Dot-dash line indicates the Continental Divide. Climate stations: GL is Grand Lake 1NW. PV and LI are the Phantom Valley and Lake Irene Snotel sites, respectively. Stream gaging stations: GD is Grand Ditch at La Poudre Pass and CR is Colorado River below Baker Gulch.

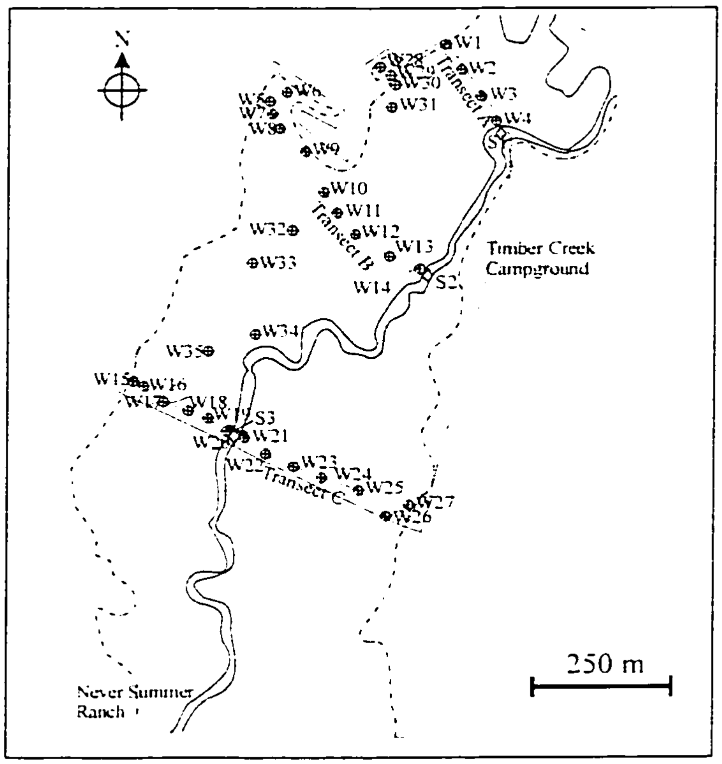

Figure 2. Map of the area between Timber Creek campground and Never Summer Ranch in the Colorado River headwaters, showing locations of monitoring wells (W1 - W35) and staff gages (S1 – S3). The gray shaded area indicates the groundwater model domain.

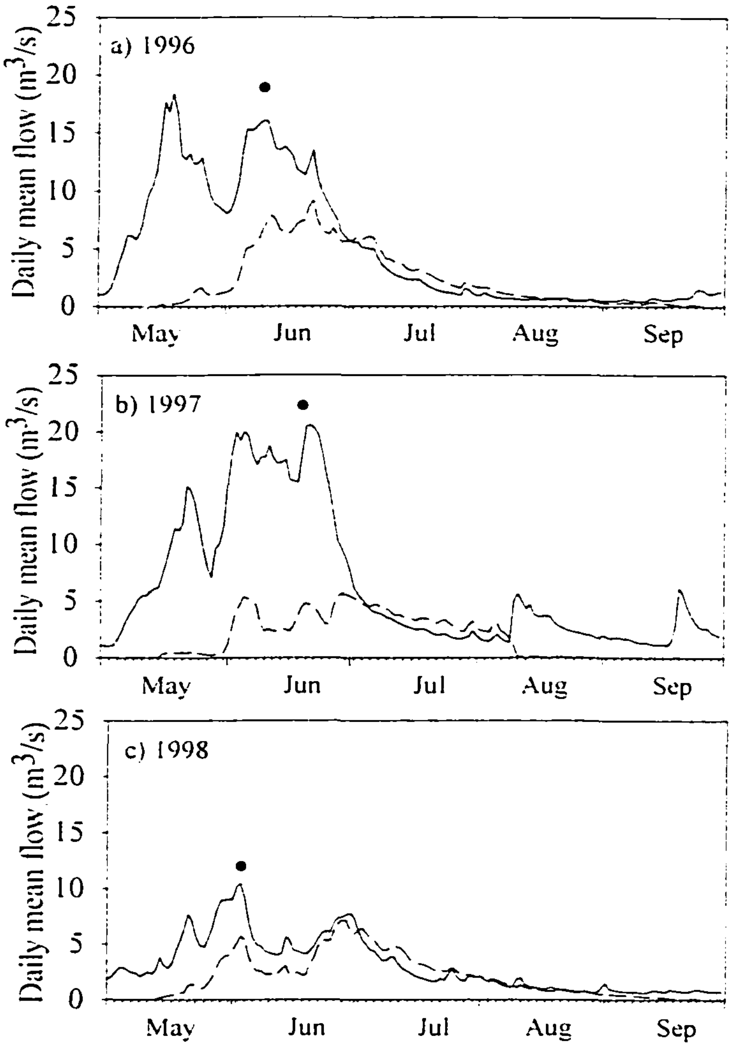

Figure 3. Daily mean flow of the Colorado River and the Grand Ditch, 1 May – 30 September in a) 1996, b) 1997 and c) 1998. Flow data are from Colorado River below Baker Gulch (solid line) and Grand Ditch at La Poudre Pass (dashed line). Black circle indicates instantaneous annual peak flow.

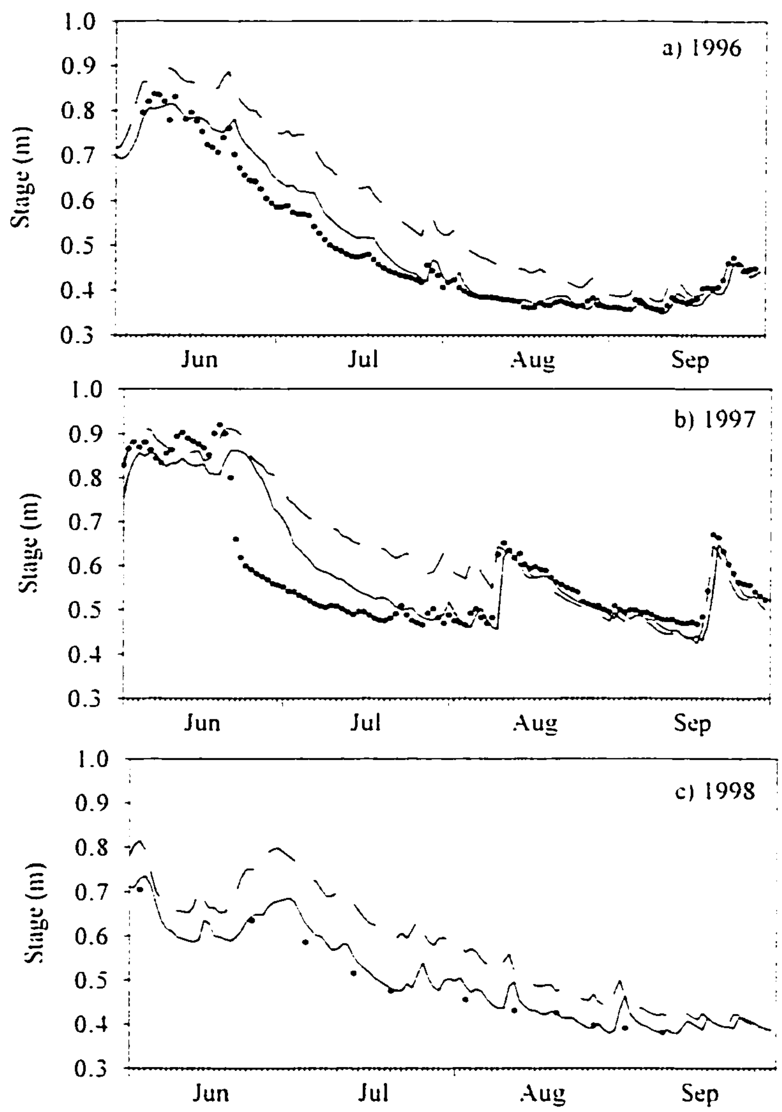

Figure 4. Stage of Colorado River near Timber Creek campground compared to predicted stage with and without diversion for 1 June – 30 September in a) 1996, b) 1997, and c) 1998. Actual stage values in 1996 and 1997 are 24 hour means based on measurements at 15 minute intervals. Actual stage values in 1998 are instantaneous manual measurements. Modeled stage is based on the relationship between stage at the Timber Creek gage and discharge at the USGS gage.

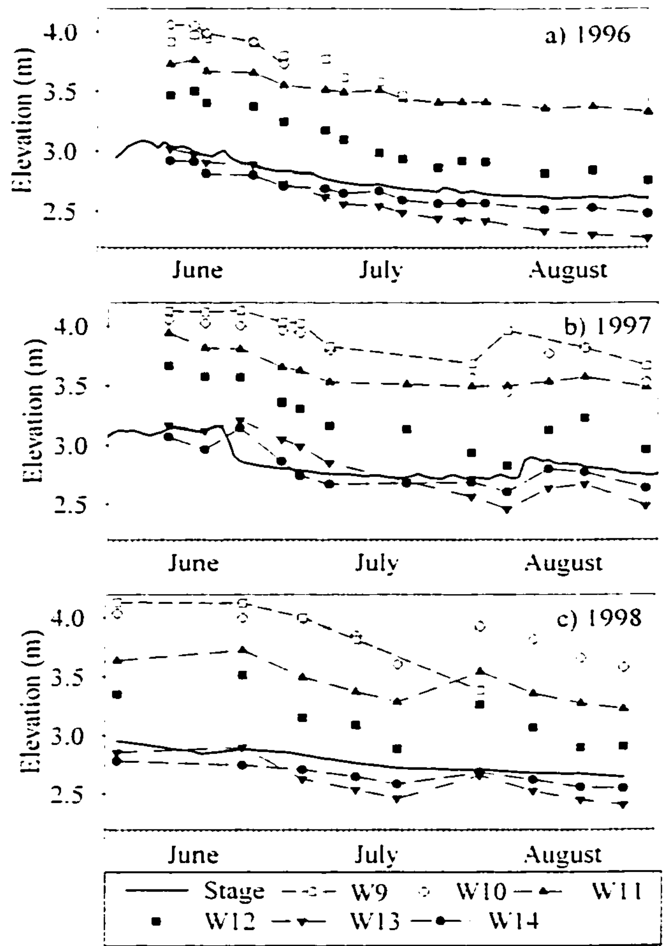

Figure 5. River stage at staff gage S2 and groundwater levels in wells W9, W10, W11, W12, W13 and W14 along transect B in a) 1996, b) 1997 and c) 1998. 1996 and 1997 stage data are from a recording gage on the Colorado River. 1998 stage data are from manual measurements at the staff gage. Elevations are relative to a local datum.

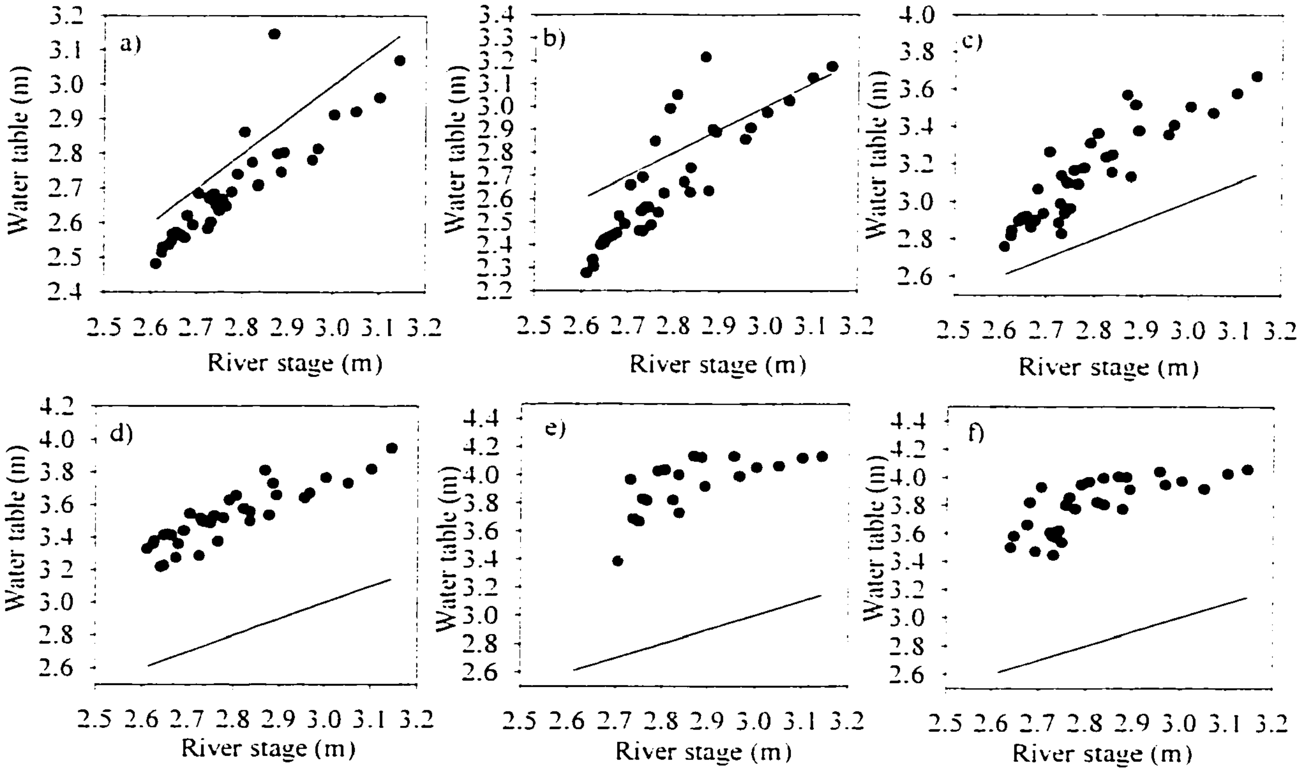

Figure 6. Scatter plots of water table elevation versus river stage for a)W14, b)W13, c)W12, d)W11, e)W10 and f)W9 along transect B. Plots include all measurements in 1996, 1997 and 1998. Lines indicate equal water table and river stage elevations.

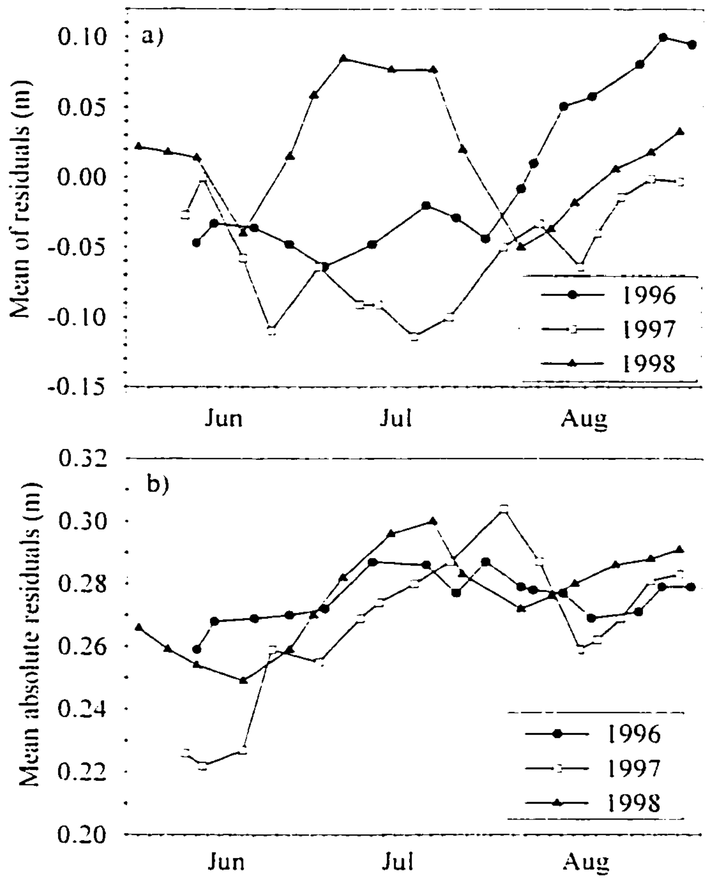

Figure 7. a) Mean of residuals and b) Mean of absolute residuals for MODFLOW transient simulations conducted in 1996, 1997 and 1998.

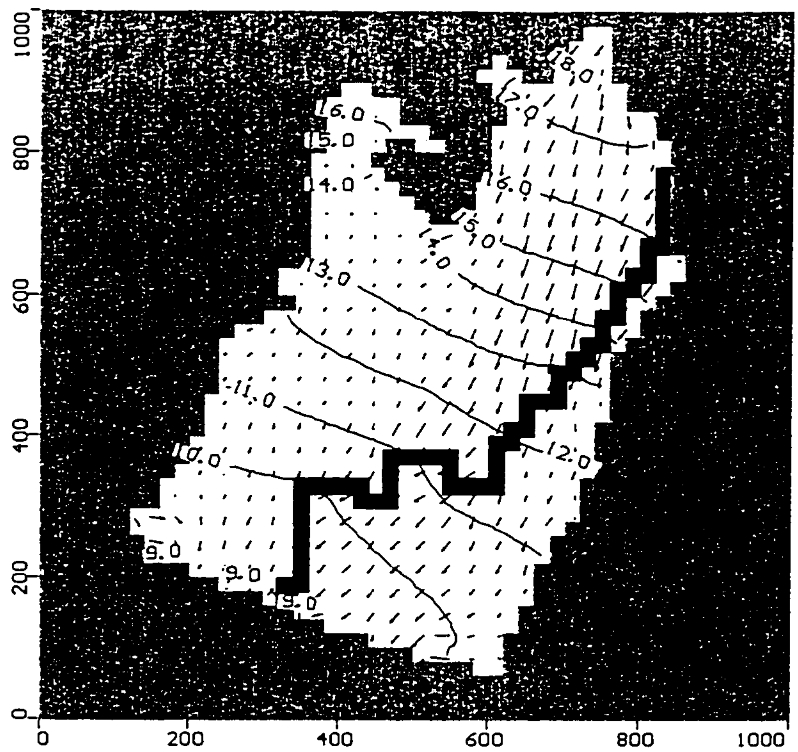

Figure 8. Potentiometric map of alluvial water table adjacent to the Colorado River between Timber Creek campground and Never Summer Ranch, 5 July 1996. Contour interval is 1.0 meter. Solid dark line is the Colorado River. Arrows are flow vectors, with length proportional to groundwater flow velocity.

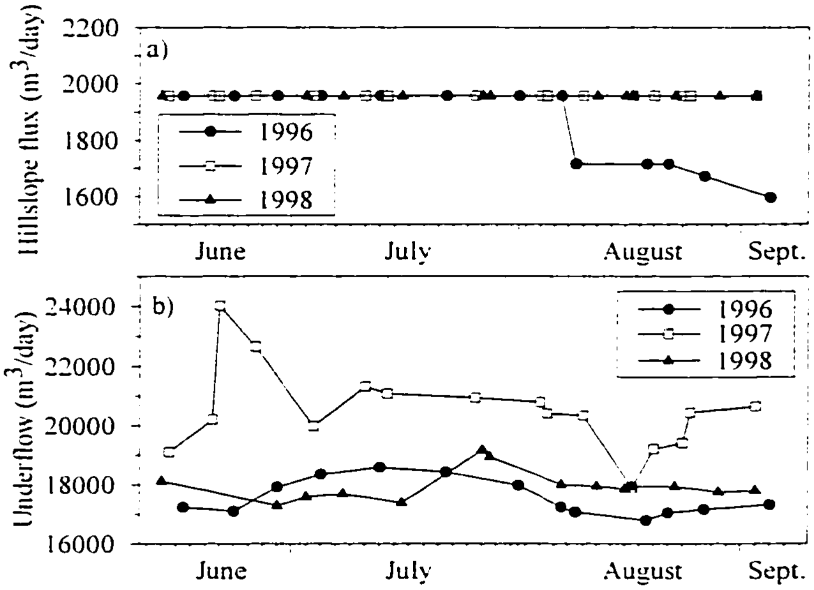

Figure 9. a) Recharge to alluvial aquifer from western hillslope, and b) down-valley groundwater flux at upstream end of study site in 1996, 1997 and 1998. Data are based on results of MODFLOW numerical groundwater flow simulations.

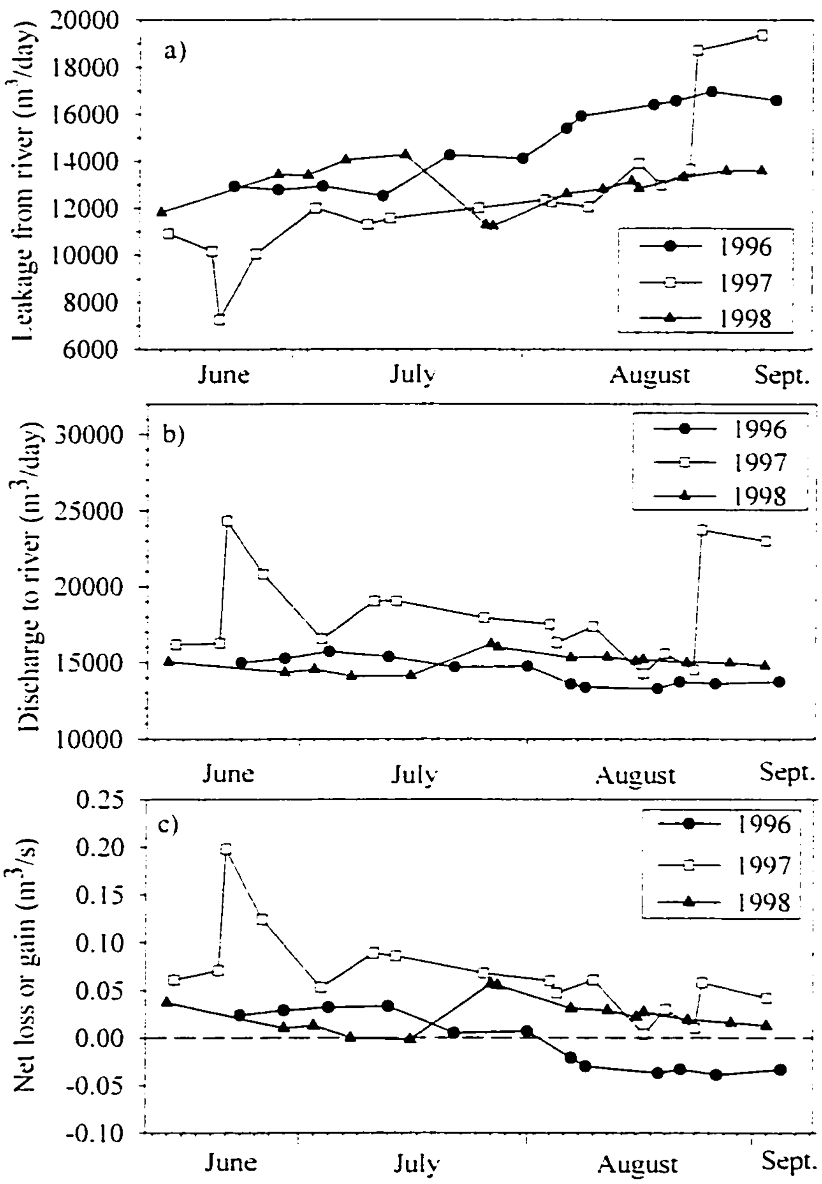

Figure 10. a) Leakage from Colorado River into the alluvial aquifer. b) Discharge to the Colorado River from the alluvial aquifer and c) net loss or gain along the study reach in 1996, 1997 and 1998. Positive values indicate a net increase in flow. Data are based on results of MODFLOW numerical groundwater flow simulations.

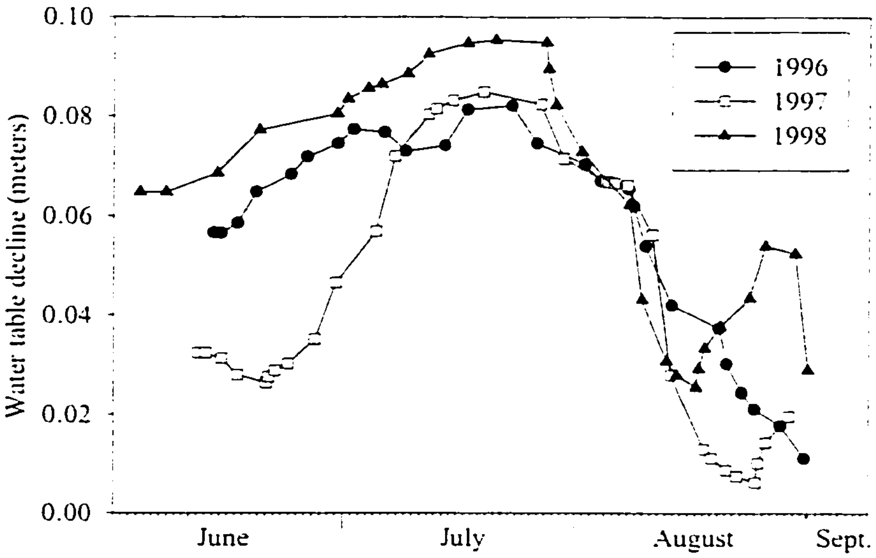

Figure 11. Calculated mean water table declines due to the Grand Ditch in all 35 wells in 1996, 1997 and 1998. Data are based on results of MODFLOW numerical groundwater flow simulations.

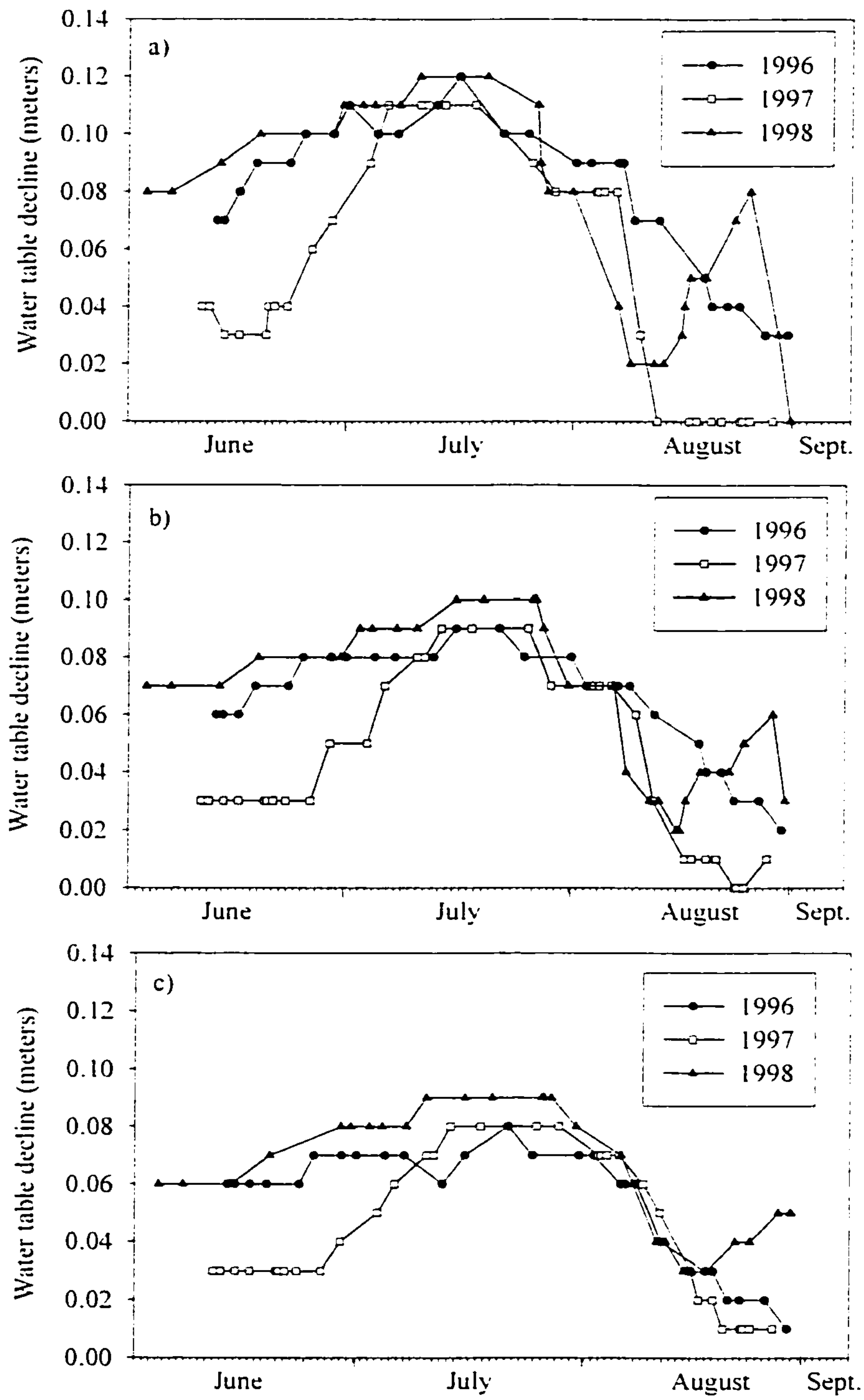

Figure 12. Calculated water table declines due to the Grand Ditch in a) well W14, b) W11 and c) W9 in 1996, 1997 and 1998. Data are based on results of MODFLOW numerical groundwater flow simulations.

3. CONTROLS ON SOIL WATER AVAILABILITY FOR WILLOW SEEDLING ESTABLISHMENT ALONG A SUBALPINE STREAM.

ABSTRACT

Establishment from seed of willows (*Salix* spp.) along Rocky Mountain streams depends largely on soil water availability. In 1999 a replicated split-split plot experiment was conducted on three gravel bars along a 200 m subalpine reach of the Colorado River to determine the effect of: 1) elevation above the water table (high, intermediate and low), 2) soil texture (sand and gravel), and 3) watering to simulate additional rainfall, on soil water availability and willow seedling establishment. These results were combined with hydrologic data to determine whether an existing flow diversion is reducing willow seedling establishment.

The mean depth to the water table in the low, intermediate and high elevation plots were all significantly different. The soil water content of the low elevation plots was significantly higher than either the intermediate or high elevation plots with the same soil texture. Plots with medium-sand soils had significantly higher soil water contents than plots with fine-gravel soils at the same elevation. There was no significant difference in soil water content between watered and unwatered plots.

First-year willow seedling survival rates were positively correlated with mean soil water content, so the highest survival rates (12-24 seedlings per m^2) occurred in the low elevation plots with sand soils, and no seedlings survived in the middle and high-elevation gravel plots. No seedlings survived in plots that had a mean soil water content of <15%, indicating that this may be a threshold for willow survival. Scour during the spring peak flow in the following year killed all of the seedlings in the low and intermediate plots. These results suggest that establishment is limited to those areas that

have sandy soils and are protected from scouring flows until a strong root system is developed.

The diversion reduced water table levels along the study reach by <1 cm to 15 cm during the 1999 growing season. The corresponding reduction in soil water content ranged from <4% in high-elevation sand plots to about 15% in low-elevation gravel plots. This decrease in soil water content had little effect on seedling survival rates. A potentially more serious impact of the diversion is the 50% reduction in the frequency of channel forming flows, as this may be causing a decrease in the area of bare soils needed for seedling establishment.

Keywords: riparian; seedling establishment; *Salix*; willow; soil water; water diversion; central Rocky Mountains; Rocky Mountain National Park.

INTRODUCTION

Cottonwoods (*Populus* spp.) and willows (*Salix* spp.) are the dominant woody riparian plants in the Rocky Mountain region of the semi-arid western United States (Patten, 1998). Riparian forests along lowland rivers of the Rocky Mountain region are dominated by Fremont cottonwood (*Populus deltoides* subsp. *wislizenii*) and narrowleaf cottonwood (*P. angustifolia* James) (Braatne et al., 1996). Willows (*Salix* spp.) replace cottonwoods as the dominant woody riparian plants at higher elevations (Patten, 1998). Although many cottonwood and willow species are capable of asexual reproduction, establishment from seed is an important recruitment mechanism (Barnes, 1983; Nhyama 1990; Langlade and Decamps, 1994). Cottonwoods and willows produce abundant small seeds that are easily dispersed by wind or by water. These seeds germinate primarily on bare mineral soil surfaces created by the erosion and deposition of alluvial sediment (Scott et al., 1996, 1997; Auble et al., 1997; Auble and Scott, 1998).

Most of the mature cottonwoods and willows along Rocky Mountain streams are phreatophytic (Alstad et al., 1999). However germination and survival rates depend on soil water availability (Fenner et al., 1984; Krasny et al., 1988; Saachi and Price, 1992; Cooper and Van Haveren, 1994). Seedlings remain dependent on soil water until the plant extends its roots to the water table, which may not occur for several years (Cooper et al., 1999). Soil water availability is controlled by factors such as elevation, frequency and magnitude of precipitation, and soil texture.

Elevation is an important control on soil water availability for two reasons. First, much of the soil water recharge along Rocky Mountain streams comes from the infiltration of snowmelt driven floodwaters. Sites near the elevation of the stream are inundated more frequently and for longer than high sites, so they receive more soil water recharge. Second, since the water table is usually at or near the elevation of the river, the depth to the water table is greater in high sites than in low sites. Since there is a general inverse relationship between water table depth and soil water content, low sites are wetter than high sites.

Riparian areas along low elevation rivers in the Rocky Mountain region receive almost no summer precipitation, and this means that cottonwood and willow seedling establishment is limited to areas where soil water is recharged by snowmelt-driven spring flooding (Scott et al., 1996, 1997). Seed rain coincides with the recession of spring peak flows, which is when the moist, bare sites needed for establishment become available (Scott et al., 1993; Johnson, 1994).

Annual precipitation generally increases with elevation in the Rocky Mountains, but most of the increase is due to a greater amount of winter precipitation. Summer rainfall is relatively similar at all elevations. However, cooler temperatures in high elevation watersheds may reduce evapotranspiration losses, so that rainfall is more effective in recharging soil water. Soil water recharge from rainfall may therefore be sufficient to support seedling establishment in high elevation watersheds. However, no studies have evaluated the effect of precipitation on soil water availability and seedling establishment in high elevation Rocky Mountain watersheds.

In general, soils with a high proportion of silt contain more plant available water than gravelly, sandy or clayey soils, and are thus more suitable for establishment. Along lower elevation streams in the Rocky Mountain region most of the floodplain sediment is either silt or sand, and seedling survival rates are higher in the silty soils (Cooper et al.

1999). Seedling survival rates in silty soils are enhanced by the fact that these soils tend to be deposited high on the floodplain, where scouring by subsequent high flows is less likely.

Most of the floodplain sediments along high elevation streams in the Rocky Mountain region consist primarily of sand and gravel and thus contain relatively little soil water. Seedling establishment may be limited to the small pockets of fine sand and silt that occur in backwater sloughs and eddies. However, no studies have evaluated the influence of soil texture on seedling establishment along high elevation streams in the Rocky Mountains.

Flow regulation by dams has resulted in a sharp decline in cottonwood seedling establishment rates along many low-elevation streams in the western U.S. (Johnson et al., 1976; Petts, 1984; Bradley and Smith,1986; Rood and Mahoney,1990; Johnson, 1992; Rood et al., 1995). One of the main factors causing the decline in seedling establishment below dams is the reduction in soil water availability due to reduced flooding, and increased water table recession rates due to sudden declines in streamflow (Mahoney and Rood, 1991).

Dams are rare along high elevation streams, but diversions are common. For example, virtually all of the headwater streams in the Upper Colorado River watershed are affected by diversions (Petsch, 1985). Although diversions do not reduce peak flows to the same extent as dams, they do cause an overall reduction in streamflow when they are in use. If soil water availability in higher elevation riparian systems depends on water table depth, then a reduction in streamflow below diversions could reduce seedling establishment rates. Conversely, flow diversions may have little effect on seedling establishment at higher elevations because soil water recharge from rainfall is sufficient to support establishment.

We investigated the effects of elevation, precipitation, and soil texture on soil water availability and willow seedling establishment along a 200-m subalpine reach of the Colorado River on the west side of Rocky Mountain National Park, Colorado (Figure 1). Streamflows along this section of the Colorado River are affected by a major water diversion structure, the Grand Ditch. This 24-kilometer diversion canal was constructed in the late 1800s to provide irrigation water for farms on the eastern side of the Continental Divide (McKnight, 1983). The Ditch intercepts the flow of eleven headwater tributaries of the Colorado River and diverts it across a low point on the Continental Divide (Figure 1). Although there is some interannual variability due to the timing of snowmelt, the Ditch usually operates from mid-May until September, and reduces streamflow and stage in the Colorado River throughout the summer.

In the 1930s the Ditch was incorporated into Rocky Mountain National Park (RMNP), but the ditch owners maintained the right to divert water (McKnight, 1983). Resource managers at RMNP are concerned that the diversion has adversely affected park wetlands and riparian areas. A specific concern is that reduced streamflow along the Colorado River have resulted in reduced willow establishment rates. Field observations over several years indicated that there were abundant mature willow stands along the study reach, but a lack of willow regeneration in the riparian valley bottom.

The objectives of the study described here were to: 1) determine whether willow seedling establishment is limited by soil water availability, 2) determine the effects of elevation, simulated rainfall, and soil texture on soil water availability and seedling establishment, 3) quantify the effect of the Grand Ditch on streamflow, stage and water table levels along the study reach during the growing season and hence, 4) determine whether the observed lack of willow regeneration can be attributed to streamflow depletion by the Grand Ditch.

STUDY SITE

The 200-meter study reach is located in the headwaters of the Colorado River in Rocky Mountain National Park, Colorado (Figure 1). Here the Colorado River flows almost directly south along a glacially formed valley known locally as the Kawuneeche Valley. The drainage area of the Colorado River at the United States Geological Survey (USGS) gauging station below Baker Gulch (USGS station no.09010500) is 138 km^2. Elevations upstream from the USGS gauging station range from 2670m to 3944m. Along the study reach the Colorado River is a gently meandering, pool-riffle channel. The channel bed is comprised of gravel and small cobbles in the riffles with sand and gravel in the pools.

The climate of the Colorado River headwaters is continental in character with local variations in temperature and precipitation caused by differences in topography and elevation (Siemer, 1977). The mean annual precipitation at Grand Lake is 51.9 cm with a standard deviation of 9.8 cm (National Weather Service Grand Lake 1NW station, 1954-2000). At Lake Irene, which is 600 m higher than Grand Lake, the mean annual precipitation is 90.8 cm with most of the difference due to greater winter precipitation (Lake Irene SNOTEL site, 1961-1990). The period with lowest precipitation is typically from late May through mid-July. In late July and early August monsoonal air flows cause high intensity, convective thunderstorms. Due to the high elevation, summers are short and the annual growing season only extends from the end of May to mid-September.

Annual runoff in the Colorado River headwaters is dominated by spring snowmelt. On average, 81% of the annual runoff occurs in May, June and July, and the mean annual peak flow of 17 m^3/s typically occurs between late May and mid-June. Flow rapidly decreases during the early to mid-summer and baseflow conditions are usually reached by mid-August. Late summer monsoon storms can cause short-term increases in runoff, but the resulting peak flows are much smaller than the spring snowmelt peak. On average, 29% of the runoff for the Colorado River above the USGS gage at Baker Gulch is diverted into the Grand Ditch (Woods 2000).

The Kawuneeche Valley contains several large subalpine riparian willow shrublands dominated by *Salix geyeriana* (Geyer's willow), *S. monticola* (mountain willow), *S. drummondiana* (silver willow) and *S. wolfii* (wolf willow). The primary sites for willow establishment are point bars and lateral bars along the Colorado River. *Picea pungens* (Colorado blue spruce) forms isolated stands on the valley floor. The driest parts of the floodplain are grasslands containing *Pentaphylloides floribunda* (shrubby cinquefoil) and *Deschampsia cespitosa* (tufted hairgrass). Colorado plant species nomenclature follows Weber and Whittmann (1996).

METHODS

HYDROLOGY

Streamflow data for the Colorado River were obtained from the USGS gauging station below Baker Gulch (station no. 09010500). Grand Ditch flow data are from a

Colorado Division of Water Resources gage at La Poudre Pass (formerly USGS station no. 09010000).

Precipitation data were obtained from the Grand Lake 1NW National Weather Service climate station, which lies 17 km south of the study site. From 15 June until 10 August rainfall was also measured using a Campbell Scientific electronic tipping bucket rain-gauge located along the Colorado River approximately 500 m downstream from the study site. These data were used to compare rainfall at the study site to the rainfall at Grand Lake. Snowfall data were obtained from the SNOTEL stations at Phantom Valley and Lake Irene (Figure 1).

EXPERIMENTAL DESIGN

A replicated split–split plot experiment was conducted on three gravel bars along the study reach in the summer of 1999 to test the effects of elevation, simulated rainfall and soil texture on soil water availability and seedling establishment. There were five replicates of the design, with two replicates on two bars and one replicate on the third bar. Each replicate consisted of four 0.25 m^2 plots at each of three elevations (high, middle and low). The high and middle elevation plots were approximately 30 cm and 15 cm, respectively, above the low plots. The low plots were installed in early July, at the onset of willow seed rain on the lowest exposed part of each bar. A monitoring well constructed from slotted 2.5-cm diameter PVC pipe was installed at each elevation to measure the water table depth. A staff gage was installed in the stream channel adjacent to each of the study bars to measure river stage. Water table depth and stream stage were measured approximately every 7 to 10 days in the early part of the study and every 3 to 5 days from mid-July until the end of August.

To determine the effect of soil texture on soil water availability and seedling establishment the top 20 cm of native soil in each 0.25 m^2 plot was replaced with either a fine gravel or a medium sand. Both of these soils were collected from the study bars. The fine gravel is the dominant soil type on the gravel bars subjected to river scour, while the medium sand represents backwater sloughs and other depositional environments with much less stream power. Two plots in each elevation treatment were filled with sand and the other two were filled with gravel. The median grain size (D_{50}) for each plot was obtained from a cumulative grain size distribution curve based on a sieve analysis of a sample collected from the plot at the end of the experiment (Gee and Bauder, 1986).

To determine the effect of rainfall on soil water availability and seedling establishment a watering treatment was applied to one sand and one gravel plot in each elevation treatment. One centimeter of water was applied to each plot every 7 to 10 days in the early part of the study and every 3 to 5 days from mid July until the end of August using a watering can. Water-drop impacts were minimized by spreading fine nylon mesh over the plot during watering, and the water was applied slowly so that there was no surface runoff. The two plots on the upstream side of each elevation treatment were assigned to the watering treatment. The two plots on the downstream side were exposed to the natural rainfall regime. The coarse nature of the soils meant that there was minimal lateral flow, so that watering the upstream plot had little or no effect on the downstream plot.

The soil water content in each plot was measured immediately prior to each watering treatment using a Moisture Point time domain reflectometry (TDR) unit with small-diameter probes (Environmental Sensors Inc., Victoria, B.C., Canada). Soil water content was recorded as the mean of three measurements in the upper 15 cm of each plot.

Seed rain was measured by installing seed traps adjacent to each of the middle and high elevation plots. The seed traps were 225 cm^2 plywood squares mounted approximately 1 meter above the soil surface, and spread with Tanglefoot®. Willow seeds were identified by size and the presence of a small cotton-like tuft. The seeds were counted and the Tanglefoot® replaced approximately weekly between mid-June and mid-July.

Willow seedlings in each plot were counted in mid-September 1999, prior to the first frost. Willow seedlings were distinguished from other seedlings by leaf shape and stem color. Since seedlings of many species were also present in the plots, it was not possible to positively identify the willow seedlings until late in the summer.

DATA ANALYSIS

The study period was divided into three time periods based upon the hydrologic conditions (Figure 2). The early period corresponded to the steep recession limb of the snowmelt hydrograph. The middle period occurred between the end of the steep recession limb and the onset of monsoon rainfall. This is typically the driest part of the summer. The late period began with the onset of monsoon rain and ended in early September.

To determine the reduction in river stage due to the Grand Ditch diversion in each period, an estimate of the undiverted discharge record was developed by summing the daily mean discharge of the Grand Ditch at La Poudre Pass and the Colorado River below Baker Gulch. Stage (S) at each of the bars, based on the manual measurements, was related to the corresponding mean daily discharge of the Colorado River at the USGS gage below Baker Gulch (Q) by a power function:

$$S = S_0 + aQ^b$$

where S_0 is the staff gage reading when Q is 0, and a and b are constants. Using the calculated undiverted flow record and the stage-discharge relationship at each bar, we calculated the undiverted stage record and compared it to the observed stage values. We also used these relationships to determine the change in the duration of inundation for each of the study plots.

Linear regression was used to relate the measured water table depth at each well to the stage measured at each bar. These linear regression relationships and the calculated undiverted stage records were used to estimate the water table if the Grand Ditch had not been operating.

A t-test was used to test the hypothesis that the mean D_{50} diameters of soils in the two soil-texture treatments were significantly different. Analysis of variance (ANOVA) was used to test for: 1) differences between water table levels in the three elevation treatments in each study period and for the entire study period, 2) differences in soil water content between treatments in each period and for the entire study period, and 3) differences in seedling density between treatments. Linear contrasts (Ott, 1993) were used to determine which treatments resulted in significant differences, and the Bonferroni adjustment was used to control the experiment-wise error rate at an alpha level of 0.05 (Ott, 1993).

RESULTS

PRECIPITATION

Winter precipitation in 1998-1999 was below average. The 1 April 1999 snow water equivalent (SWE) at Phantom Valley was 14.5 cm, or 63% of average. At Lake Irene the 1 April SWE was 59.9 cm or 91% of average. Summer precipitation at Grand Lake 1NW from 1 June through 31 August 1999 was 20.5 cm, which is 137% of the 51-year average. The monthly total for June (3.6 cm) was only 87% of average, but the totals for July (8.4 cm) and August (8.5 cm) were 157% and 154% of average, respectively. The July rainfall total at the rain gage installed near the study site was 7.8 cm, indicating that the monthly rainfall totals are similar to Grand Lake 1NW. However daily rainfall values at this gage were not correlated with those at Grand Lake 1NW (Pearson correlation coefficient $r = 0.024$). Thus, while the Grand Lake 1NW station data are useful for interannual comparisons, they are not representative of individual storms at the study site.

STREAMFLOW AND STAGE

The instantaneous annual peak flow of the Colorado River for water year (WY) 1999 was 13.9 m^3/s and occurred on 23 June. This peak flow has a recurrence interval of approximately 1.5 years, which is reported to be the recurrence interval of the bankfull flow in many alluvial rivers (Wolman and Miller, 1960). The low elevation study plots were inundated at peak stage but the high and middle elevation plots were not. The low elevation plots were all exposed by the first week of July. Flows declined throughout the summer and reached a low of 0.93 m^3/s in mid-August.

In WY1999 water was diverted by the Grand Ditch from 28 May until 3 September (Figure 2). In June, July and August, the Ditch diverted 36%, 50% and 39%, respectively of the total monthly discharge of the Colorado River at the USGS gage below Baker Gulch. Daily flows were reduced by up to 59%. Between 1 June and 31 August 2.4×10^7 m^3 was diverted and this was 41% of the total discharge of the Colorado River at the USGS gage. These values are close to the 45-year mean values of 2.0×10^7 m^3 and 39%, respectively.

The diversion of streamflow into the Grand Ditch reduced the stage of the Colorado River at the study site by 5-10 cm during most of the early and middle study periods (Figure 3). The calculated undiverted peak stage in late June would not have been high enough to inundate any of the middle or high plots. However, the low plots would have been inundated for 9 to 11 days longer, until 14 July. The maximum reduction in stage was 13 cm and occurred in mid-July. By the end of the late period in late August the observed stage values were less than 1 cm below the calculated undiverted stage.

WATER TABLE DEPTH

Both the highest water table levels and the most rapid declines were observed during the early period (Table 1 and Figure 4). From 1 to 15 July water table levels in the middle and high elevation plots decreased by 4.0 to 7.9 mm/day, with a mean decline of 6.0 mm/day. River stage increased by approximately 3 cm from 13 July to 15 July due to a combination of rainfall and increased snowmelt. Over this same period the water table levels in the study plots increased by an average of 2.9 cm.

The rate of water table decline decreased slightly during the middle period. The mean rate of decline was 3.8 mm/day, and values ranged from 2.8 to 5.1 mm/day. The water table declined at a similar rate during the first two weeks of the late period, and the lowest water tables of the summer were recorded in mid-August (Figure 4). Water tables increased by 3 to 5 cm in the last two weeks of August in response to a similar rise in the level of the Colorado River. The difference between the maximum and minimum water table levels in July and August ranged from 13.8 to 32.5 cm with a mean of 23.3 cm (S_x = 1.4 cm). Water table levels were significantly different ($p<0.010$) between all three of the elevation treatments in all three periods of the study (Table 2).

Water table depths in 15 of the 16 plots were highly correlated with river stage (Table 3), indicating that reductions in stream stage also lowered the water table in these plots. The only plot for which water tables were not significantly correlated with river stage was M3 (R^2=0.53, p=0.163). Water levels at M3 were closely related to stream stage in the early period, but remained almost constant in the middle and late periods, indicating that the well screen had become blocked. Based on the regression results presented in Table 3, water tables in the plots were reduced by up to 15 cm in the early and middle periods. However by the end of the late period the estimated undiverted water table depths were almost equal to the observed water table depths.

SOIL TEXTURE

The D_{50} of the fine gravel soils ranged from 1.4 mm to 3.2 mm, with a mean of 1.8 mm (S_x =0.13 mm). The D_{50} of the fraction less than 2 mm diameter ranged from 0.65 mm to 0.99 mm with a mean of 0.81 mm (S_x = 0.03 mm). The D_{50} of the medium sand soils ranged from 0.36 to 0.57 mm, with a mean of 0.42 mm (S_x = 0.01 mm). None of the particles in the sand soils were greater than 2 mm in diameter. The mean D_{50} for the fraction <2 mm in the fine gravel and the medium sand were significantly different (two-tailed t-test, $p < 0.0001$).

SOIL WATER CONTENT

The highest soil water content in most of the plots occurred in early July, and the lowest soil water contents occurred in early August (Figure 5). For the study period as whole, the high and medium elevation gravel plots generally had soil water contents of less than 10%, while soil water contents in the low elevation gravel plots ranged from 16 to 39% (Figure 5a). The soil water content of the high and medium sand plots ranged from 18 to 40%, while the soil water content in the low elevation sand plots ranged from 44 to 52% (Figure 5b).

The soil water content in all plots declined throughout the middle period. The largest decrease occurred in low elevation gravel plots where the mean soil water content decreased by 12%. The soil water content in late July ranged from less than 5% in high elevation gravel plots to more than 20% in low elevation sand plots (Figure 5). Soil water content increased in the late period, apparently due to rainfall recharge. The increases ranged from < 3% in low elevation sand plots to > 7% in low elevation gravel plots.

The soil water content of sand plots was significantly higher than gravel plots at the same elevation in all three study periods ($P < 0.0001$) indicating a significant control of soil water by texture (Figure 5). In particular, during the middle period, the mean soil water content of high-elevation sand plots was up to 15 times greater than the paired gravel plots (Figure 5).

The mean soil water content of the low elevation plots was significantly higher than the middle and high elevation plots for both soil textures in all periods (Table 4). The mean soil water content of middle elevation plots was always higher than the corresponding high elevation plots, but none of the differences were statistically significant (Table 4).

Soil water content was inversely related to height above the water table in both soil types (Figure 6). However the soil water content of the gravel plots declined more sharply than that of the sand plots, particularly as the water table depth increased from 0 to 25 cm. The soil water content of the gravel plots was always less than 15% when the water table was more than 25 cm below the surface. In contrast, the soil water content of the sand plots remained generally higher than 15% even as the water table depth increased to more than 50 cm below the surface.

There were no statistically significant differences ($P > 0.5690$) in the soil water content of watered and unwatered plots during the study period.

SEED RAIN AND SEEDLING DENSITY

Seed rain began immediately after the peak flow in late June and continued for approximately two weeks (Figure 2). The highest seed density was 133 /m^2 for a single trap. Three of the ten seed traps did not contain any seeds.

Seedling densities at the end of the growing season ranged from 0 in all of the medium and high elevation gravel plots to 48/m^2 in one of the low elevation sand plots. Mean seedling densities ranged from 0 in the medium and high gravel plots to 18/m^2 in the low elevation sand plots. There were no significant differences due to the watering treatment for any of the plots, so watered and unwatered plots were pooled for the analysis of effects due to soil texture and elevation.

Low and middle elevation sand plots had significantly higher seedling densities than the paired gravel plots (P = 0.0002 for both). The mean seedling density in low elevation sand plots was more than five times greater than in the corresponding gravel soil plots (Figure 7). The mean seedling density in high elevation sand plots was greater than high elevation gravel plots, but the difference was not statistically significant (P = 0.074).

Mean seedling densities in low elevation plots were higher than in the paired medium and high elevation plots, but only the contrast between low and high elevation plots with sand soils was statistically significant (P = 0.001). Middle elevation plots with sand soils had a higher mean seedling density than the corresponding high elevation plots, but the difference was not statistically significant (P = 0.038). The highest seedling densities were in plots that had higher soil water contents, and no seedlings survived in plots where the mean soil water content was less than 15% (Figure 8).

DISCUSSION

EFFECT OF SOIL WATER AVAILABILITY ON SEEDLING ESTABLISHMENT

Soil water availability appeared to limit willow seedling establishment within the range of soil textures tested. Although there was a great deal of variability, seedling densities in both sand and gravel plots were positively correlated with mean soil water content. Since there were no seedlings in either sand or gravel plots with a mean soil water content < 15% in July and August, this soil water content may be a threshold for seedling survival in these soil types.

These results are consistent with previous studies of the effect of soil water availability on willow seedling establishment. Nearly 100% of *Salix lasiolepis* seedlings died in unwatered plots along a northern Arizona stream, while much lower mortality rates occurred in watered plots (Saachi and Price, 1992). Supplemental watering increased survival rates of *Salix alaxensis* seedlings on placer-mine tailings in interior Alaska (Cooper and Van Haveren, 1994). Germination rates of *Salix interior* (sandbar willow) and *Salix alaxensis* (feltleaf willow) on the Tanana River floodplain in Alaska were positively correlated with soil water availability (Krasny et al., 1988). Although the Arizona site represents a harsher physical environment than our study site due to the high summer temperatures, the Alaskan sites are comparable in terms of temperature and precipitation.

FACTORS CONTROLLING SOIL WATER AVAILABILITY

Soil texture and elevation above the water table were the two significant controls on soil water content in the study plots. Most of the bars along the Colorado River are comprised of sediments similar in texture to our gravel plots. Figure 6 shows that the soil water content of these gravel plots decreased rapidly as the water table depth increased from 0 to 25 cm. For water table depths greater than 25 cm the soil water content was generally below 15%, which appears to be a threshold for willow seedling survival. Since all of the medium and high elevation plots had water table depths greater than 20 cm for most of the summer, the implication is that most of the bar surfaces are unsuitable for willow seedling establishment. Recruitment of willows into these gravelly portions of the floodplain may only occur by vegetative means.

Sandy sediments occur in backwater sloughs and eddys, and are similar in texture to our sand plots. Figure 6 shows that the sand plots generally retained more than 15% soil water even as the water table depth exceeded 50 cm. Since most areas on the floodplain are within 50 cm of the water table, this suggests that almost any sandy site is potentially suitable for establishment. However, sandy sites occupy a very small proportion of the total floodplain.

Due to the effects of water table depth and soil texture on soil water content, sand plots at lower elevations supported the greatest number of seedlings. This suggests that during the first summer after germination, the most suitable sites for survival are sandy areas near the stream. However, subsequent field observations indicated that spring runoff and high stream flows in 2000 eroded most of the 1999 seedlings from the low and middle elevation study plots. Thus, although first-year seedling survival was highest in the low elevation sand plots, the longer term survival of willows along Rocky Mountain streams may be limited to sandy sites that are protected from floods until the plant develops a strong root system. These sites may be in areas high enough above the river so that flood events are relatively rare. Suitable establishment sites may also be created by events such as channel abandonment and the draining of abandoned beaver ponds.

The non-significant effect of our watering treatment on soil water content suggests that, at least during 1999, rainfall did not help maintain higher soil water contents. However, soil water contents in the plots increased during August while the water-table was dropping, and this increase can only be ascribed to rainfall. Also, seedling densities in some of the watered plots were higher than in the corresponding unwatered plots, suggesting that there was more soil water available to seedlings in the watered plots. This apparent ambiguity may be due to two factors. First, the soil water contents indicated by the TDR method represent an integrated value for the 0-15 cm depth interval. First-year willow seedlings excavated from near the plots had root systems that were less than 5 cm long. Thus, while the watering treatment had no significant effect on soil water in the 0-15 cm depth interval, it apparently increased the soil water content of the 0-5 cm interval sufficiently to increase willow seedling survival. Second, the soil water measurements were made several days after the watering treatment, and immediately prior to the next watering treatment. While this was unavoidable due to the time needed to measure soil water contents in all 60 0.25 m^2 plots, it minimized the effect of the watering treatment.

EFFECT OF THE GRAND DITCH ON WILLOW SEEDLING ESTABLISHMENT

Central to our investigation was whether the Grand Ditch diversion has reduced willow seedling establishment by reducing soil water availability in potential establishment sites. We hypothesized that soil water availability in the riparian corridor is being reduced due to (1) lower peak stage resulting in reduced initial recharge, (2) lower stage resulting in deeper water tables in the riparian zone throughout the summer.

Peak stage at the study sites was reduced by approximately 10 cm in 1999. Even the estimated undiverted peak stage would not have inundated the middle and high plots. Thus, in a year with a moderate peak flow, the diversion had relatively little effect on the area of riparian soils recharged by flood-waters. Because the stage-discharge relationship is a power function, the diversion would have less of an effect on peak stage in years with a higher peak flow.

The decrease in July and August water tables in the riparian zone is of potentially greater importance. The Grand Ditch diverts approximately 50% of the Colorado River flow during this time, and the calculated reductions in stage during the 1999 growing season ranged from <1cm to 15 cm. Figure 6 indicates that the decrease in soil water content resulting from a water table decrease of 1-15 cm would vary depending on the soil type and height above the water table. Hence the decrease in mean soil water contents due to the Grand Ditch range from less than 4% in the high-elevation sand plots to about 15% in the low-elevation, gravel plots. Figure 8 indicates that these decreases would probably not have a major effect on willow establishment rates in a wet year like 1999. However, in a drier year with less summer precipitation the effect of the Ditch on river stage could be more important.

The Grand Ditch diversion may be having other effects on willow seedling establishment in addition to the reduction in soil water availability. Many of the pioneer species that colonize floodplain sites are shade intolerant (Rood and Mahoney, 1990; 1995). The creation of unvegetated bars is therefore a critical pre-cursor for willow colonization. The channel-forming flows in subalpine streams in Colorado range from 0.8 to 1.6 times the bankfull flow (Andrews and Nankervis, 1995). The Grand Ditch diversion has reduced the frequency of flows in this range by approximately 50% (Woods, 2000). This reduction in the frequency and magnitude of geomorphic disturbance could potentially reduce seedling establishment rates even more than the observed reduction in soil water availability.

Another potential limitation on willow establishment is the decline of beavers in Rocky Mountain National Park. Although census data are limited, beaver populations along the Colorado River and other streams in Rocky Mountain National Park have declined considerably since the early 1900s. Riparian wetlands in the study area contain hundreds of abandoned beaver dams, but in 1999 only six active colonies were found (Dr. B. Baker, USGS, pers. comm.). Beavers colonize and abandon sites on a periodic basis in response to the availability of vegetation for food and dam building material (DeByle, 1985). The breakdown of abandoned dams lowers upstream water levels and exposes areas of bare moist sediment that are potential willow establishment sites. The low beaver population in the study area means that the cycle of colonization and abandonment is presently limited to just a few small areas.

CONCLUSIONS

First-year willow seedling survival rates on gravel bars along the upper headwaters of the Colorado River were positively correlated with soil water availability. No seedlings survived in plots with a mean soil water content of $<15\%$ indicating that this may be a threshold for seedling survival.

The soil water content of low elevation plots was significantly higher than either the intermediate or high elevation plots with the same soil texture. Plots with medium-sand soils had significantly higher soil water contents than plots with fine-gravel soils at the same elevation. Therefore spatial variations in soil water availability due to elevation above the water table and soil texture are important controls on seedling establishment. Although summer rainfall may help to maintain the soil water content of riparian soils, this study did not demonstrate such an effect.

Due to the predominance of gravelly soils and the correspondingly low soil water content, most sites on gravel bars are unsuitable for establishment. Establishment is probably limited to sites that have sandy soils and are protected from flooding until the plant develops a stronger root system. These sites may be in areas high enough above the river so that flood events are relatively rare. Suitable establishment sites may also be created by channel abandonment and the draining of abandoned beaver ponds.

By reducing river stage and water table levels along the Colorado River the Grand Ditch has reduced the availability of soil water on gravel bars. While this decrease in soil water availability probably does not have a major effect on willow establishment rates in wetter years, it could be more important in a drier year. The Ditch has also reduced the frequency and magnitude of geomorphic disturbance along the Colorado River, and this could potentially reduce seedling establishment rates even more than the observed reduction in soil water availability.

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Table 1. Range, mean and standard deviation (SD) of water table depths for high, middle and low study plots in early, middle and late phases of the study. All values are in centimeters.

	Early phase (1 – 15 July)			Middle phase (16 July – 3 August)			Late phase (4 –31 August)		
	Range	Mean	SD	Range	Mean	SD	Range	Mean	SD
High	30.4-36.9	33.4	3.0	37.5-50.8	44.1	5.6	41.1-55.6	48.0	5.9
Middle	15.8-25.5	21.5	3.9	23.7-35.7	31.2	5.4	27.4-38.4	34.3	4.5
Low	2.8-5.3	4.3	1.1	8.5-18.3	14.3	3.7	12.2-21.6	18.6	3.8

Table 2. P-values determined from linear contrasts to compare mean water table levels in high, middle and low study plots in early, middle and late phases of the study and for the whole study period.

Comparison	Early	Middle	Late
High vs. Middle	**0.002**	**0.004**	**0.002**
High vs. Low	**<0.001**	**<0.001**	**<0.001**
Middle vs. Low	**0.003**	**0.004**	**0.010**

Table 3. Results of linear regression analyses of depth to water table (D_w in centimeters) versus measured stage value (S in centimeters) for each plot. H, M and L represent the high medium and low plots respectively. B_0 and B_1 are the intercept and slope of the regression, respectively. S_x is the standard error of the regression. P-values are for the null hypothesis that the slope of the regression is equal to zero.

Plot No.	B_0	B_1	R^2	S_x	P values
H1	6.43	1.21	0.967	0.67	<0.0001
M1	-3.49	1.14	0.972	0.60	<0.0001
L1	-24.60	1.39	0.900	1.20	<0.0001
H2	8.15	1.05	0.971	0.54	<0.0001
M2	-5.91	1.07	0.974	0.52	<0.0001
L2	-20.80	1.29	0.971	0.66	<0.0001
H3	9.38	0.84	0.920	1.23	<0.0001
M3	-1.46	0.83	0.529	1.40	0.163
L3	-24.00	0.89	0.980	0.66	<0.0001
H4	12.20	0.84	0.901	1.39	<0.0001
M4	5.77	0.64	0.963	0.59	<0.0001
L4	-22.50	0.85	0.957	0.93	<0.0001
H5	16.80	1.02	0.956	0.67	<0.0001
M5	7.08	0.99	0.949	0.67	<0.0001
L5	-15.30	0.93	0.943	0.71	<0.0001

Table 4. P-values for linear contrasts to compare soil water contents in high, middle and low elevation treatments. Treatments are identified by a three-letter code. The first letter denotes the elevation treatment (H is high, M is middle and L is low), the second letter denotes texture (S is sand, G is gravel) and the third letter denotes watering (W is watered, U is unwatered). Statistically significant results are shown in bold type.

Treatment	Period		
	Early	Middle	Late
HSW vs MGW	0.0097	0.0485	0.0542
HSW vs LSW	**<0.0001**	**<0.0001**	**<0.0001**
MSW vs LSW	**<0.0001**	**<0.0001**	**<0.0001**
HGW vs MGW	0.0344	0.4475	0.5093
HGW vs LGW	**<0.0001**	**<0.0001**	**<0.0001**
MGW vs LGW	**<0.0001**	**<0.0001**	**<0.0001**
HSU vs MSU	0.0381	0.0576	0.2539
HSU vs LSU	**<0.0001**	**<0.0001**	**<0.0001**
MSU vs LSU	**<0.0001**	**<0.0001**	**<0.0001**
HGU vs MGU	0.1450	0.5531	0.7738
HGU vs LGU	**<0.0001**	**<0.0001**	**<0.0001**
MGU vs LGU	**<0.0001**	**<0.0001**	**<0.0001**

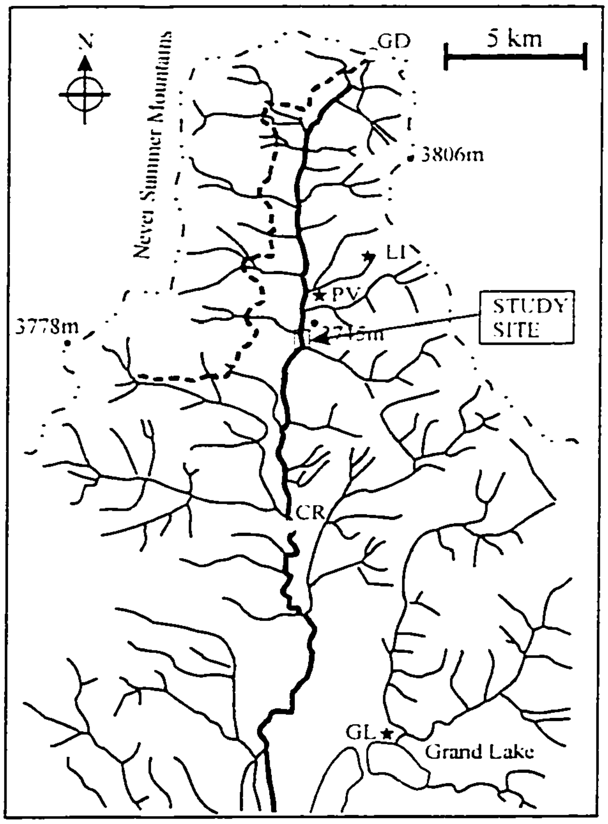

Figure 1. Map of Colorado River headwaters near Grand Lake, Colorado. The thick solid line is the main stem of the Colorado River, and the thinner solid lines are tributary streams. The dashed line is the Grand Ditch. Dot-dash line indicates the Continental Divide. Climate stations are indicated by solid stars: GL is Grand Lake 1NW, PV and LI are the Phantom Valley and Lake Irene Snotel sites, respectively.

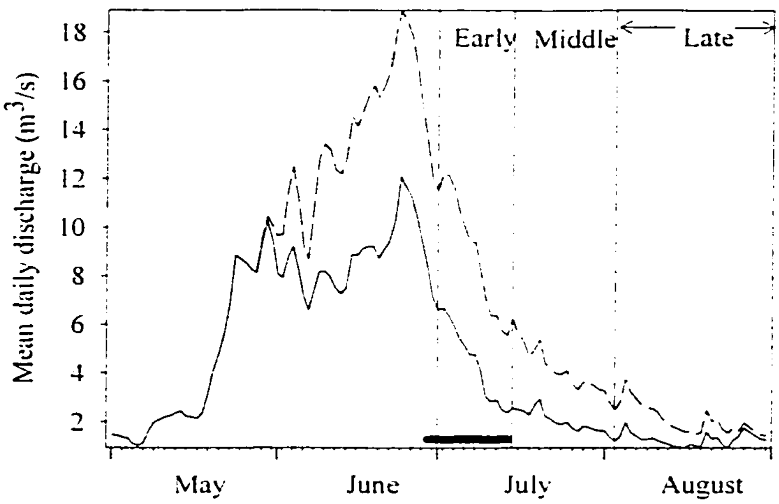

Figure 2. Daily mean flow (m^3/s) of Colorado River below Baker Gulch (solid line) and summed daily mean flows of Colorado River and Grand Ditch at La Poudre Pass (dashed line) from 1 May to 1 September 1999. Vertical lines indicate study periods. Thick solid line indicates the period of willow seed rain.

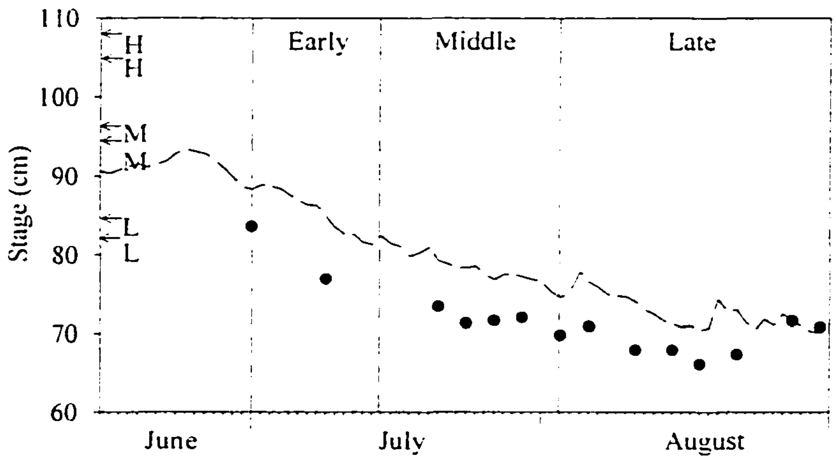

Figure 3. Calculated undiverted stage record (solid line) and measured stage values (•) at one of the three study bars along the Colorado River from 15 June to 1 September 1999. Arrows on y-axis indicate the ground surface elevations in high (H), medium (M) and low (L) plots in replicates 1 and 2.

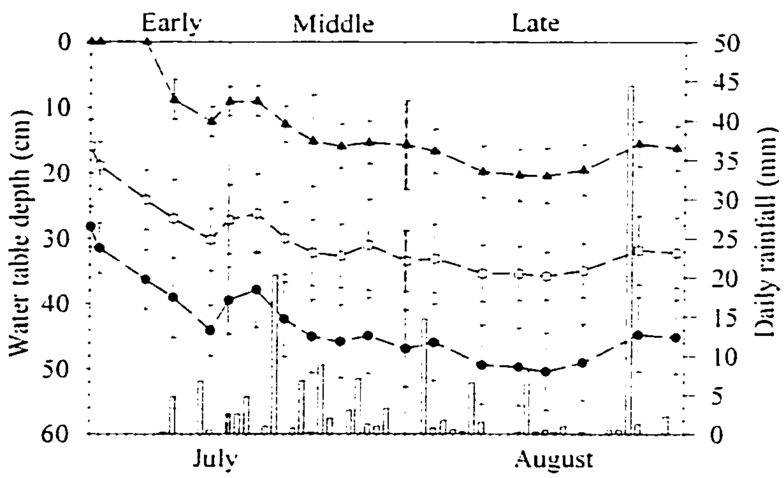

Figure 4. Depth of water table in high (●), middle (□) and low (▲) plots (cm) and precipitation at study site (mm), 1 July – 1 September 1999.

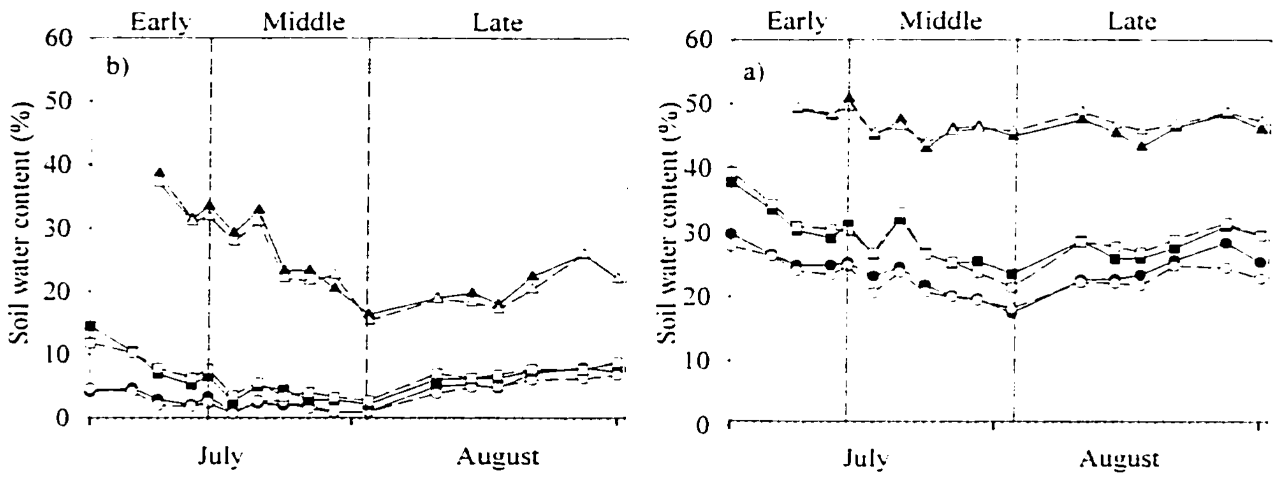

Figure 5. Volumetric soil water content (percent by volume) in high (●), middle (■) and low (▲) plots for a) fine-textured soils and b) coarse textured soil plots, 1 July - 1 September 1999. Solid symbols indicate unwatered plots and open symbols indicate watered plots.

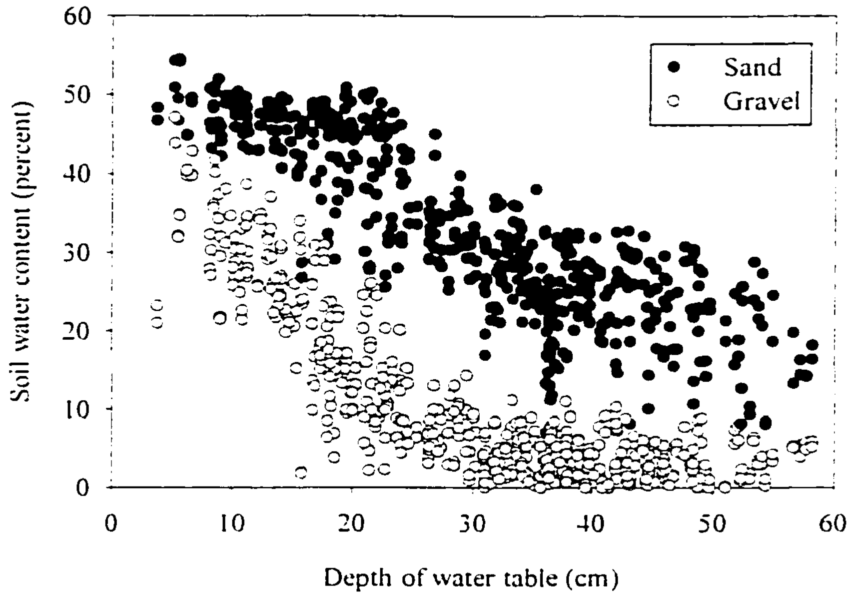

Figure 6. Plot of soil water content (percent by volume) versus water table depth (centimeters) in sand and gravel plots.

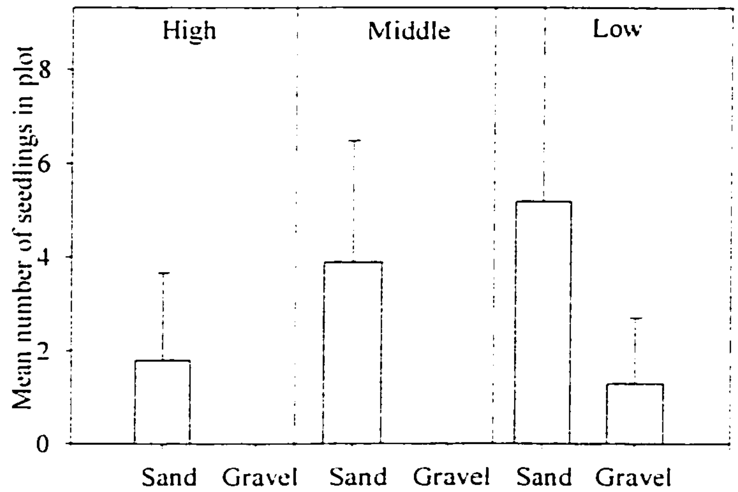

Figure 7. Seedling densities in plots in mid-September 1999. No seedlings were present in high or middle elevation coarse-textured soil plots.

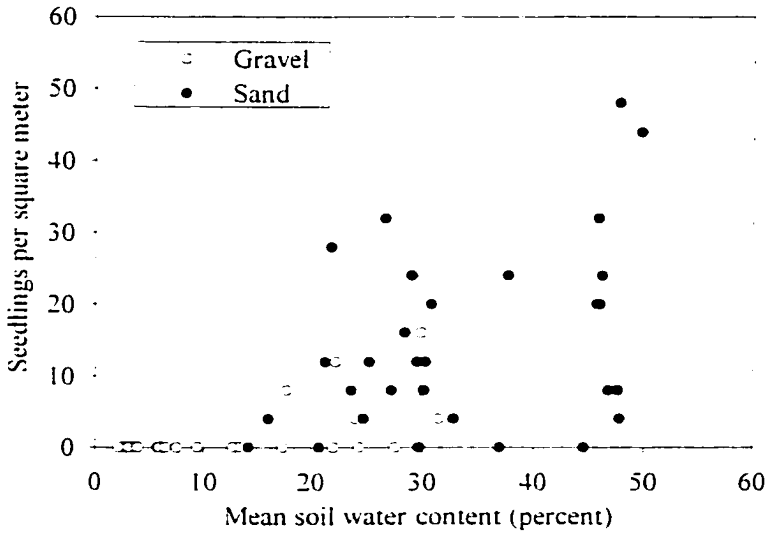

Figure 8. Plot of seedling density (m^2) versus mean soil water content (percent by volume) in sand and gravel plots.

4. HYDROLOGY OF A SUBALPINE TOESLOPE WETLAND IN ROCKY MOUNTAIN NATIONAL PARK, COLORADO.

ABSTRACT

Wetlands in the central Rocky Mountains only occur in landscape positions where they receive surface water or groundwater inflows. Toeslope wetlands occur at the base of hillslopes, where the sudden change in gradient causes exfiltration from the hillslope aquifer. Toeslope wetlands also occur around the perimeter of alluvial fans, but this type of toeslope wetland has not been documented in the literature. This paper reports on a two-year study of the Lost Creek alluvial fan toeslope wetland in Rocky Mountain National Park. The primary objectives were to: 1) investigate the hydrology of the wetland, and 2) determine the hydrologic effect of an existing streamflow diversion.

Surface water from Lost Creek provided more than 90% of the inflows to the Lost Creek wetland in the early summer. A series of three gauging stations along the alluvial fan showed that up to 25% of the flow in Lost Creek was lost to seepage. Nested piezometers and monitoring wells confirmed that this seepage was the primary source of recharge to the alluvial fan aquifer. When flow in Lost Creek suddenly stopped due to the diversion there was a rapid decline in groundwater gradients, a water level decline of up to 75 cm in some areas of the wetland, and a cessation of flows from springs at the lower margin of the alluvial fan. Conversely, the diversion of water into Lost Creek rapidly reversed these changes. These results show that seepage from Lost Creek is critical for sustaining water levels in the alluvial fan aquifer and this aquifer in turn is critical for sustaining groundwater flow into the toeslope wetlands around the margin of the Lost Creek alluvial fan. The importance of streamflow as a source of wetland recharge means that alluvial fan toeslope wetlands are a hydrologically distinct type of toeslope wetland.

The close connection between surface water and groundwater in alluvial fan toeslope wetlands means that streamflow diversions can adversely affect wetlands that are not immediately adjacent to the stream.

Keywords: subalpine wetlands; wetland hydrology; stream – groundwater interactions; streamflow diversions; central Rocky Mountains; Rocky Mountain National Park.

INTRODUCTION

The central Rocky Mountains of the western United States have a continental climate characterized by cold winters and warm, dry summers (Siemer, 1977). Winter precipitation falls as snow, and most of the annual runoff occurs during spring snowmelt. Summer precipitation occurs primarily as brief, convective thunderstorms, and there are often periods of several weeks with no rain. Evapotranspiration rates usually exceed precipitation throughout the summer. Consequently, wetlands in the central Rocky Mountains are limited in spatial extent, and only occur in landscape positions where they receive surface water or groundwater inflows (Cooper, 1990).

Riparian wetlands in the central Rocky Mountains occur along montane and subalpine streams with broad alluvial valleys, and are supported by inflows from snowmelt and hillslope runoff in addition to water from the stream (Ruddy and Williams, 1991). A second group of central Rocky Mountain wetlands occurs in moraine and bedrock-dammed depressions formed during the glacial advances of the late Pleistocene. These depression wetlands receive inflows from hillslope runoff, in-situ snowmelt and summer rainfall (Cooper, 1990). A third group of wetlands occurs on or at the foot of slopes, particularly around the margins of alluvial fans. Their position in the landscape suggests that these toeslope wetlands are supported primarily by hillslope runoff. Almost all of the inflow to toeslope wetlands in an alpine cirque in Rocky Mountain National Park came from an adjacent talus slope (Bachmann, 1994). However, there have been almost no hydrologic studies of toeslope wetlands in the central Rocky Mountains.

Although they occupy just a small fraction of the landscape, wetlands are a critical part of the central Rocky Mountains ecosystem. Wetlands provide critical habitat for amphibians and birds, and riparian shrubs such as willow (*Salix* spp.) provide forage for many species including moose and elk (Berry et al., 1997). Many depression wetlands and toeslope wetlands in the central Rocky Mountains are fens (Cooper, 1990). These fens are ecologically important for two reasons. First, they are among the most southerly boreal peatlands in North America (Malterer, 1996). Second, they are older than most other boreal peatlands; many have basal carbon dates of between 8000 and 12000 YBP (Chimner, 2000). Since peat accumulation rates are related to temperature, the stratigraphy of central Rocky Mountain fens provides a valuable record of climate change during the Holocene.

The dependence of central Rocky Mountain wetlands on surface water and groundwater inflows means that they are potentially vulnerable to man-made hydrologic modifications such as ditches, drains and water diversions. In recent years there has been a substantial increase in the population of the central Rocky Mountain region, mainly due to domestic migration and immigration from other countries. In the 1990s five of the ten fastest growing counties in the United States were in the Front Range of Colorado, at the eastern edge of the central Rocky Mountains (U.S. Census Bureau, 2000). This rapid population growth has resulted in increasing pressure to use more of the water from streams flowing out of the Rocky Mountains to supplement existing water supplies. However, most of the region's streams are already heavily appropriated. Colorado in particular has numerous stream diversions that withdraw water from mountain streams and transport it to the region's more densely populated areas (Petsch, 1985). There is concern that existing and future withdrawals from central Rocky Mountain streams could adversely affect the region's wetlands. However, a lack of hydrologic studies in central

Rocky Mountain wetlands currently limits the ability of water resource managers to assess and predict the effects of water diversions.

Previous studies of the impacts of water diversions on central Rocky Mountain wetlands focused entirely on riparian systems, and came to different conclusions. A study of the potential hydrologic impact of a diversion on subalpine riparian wetlands along the South Fork of the Williams Fork in Colorado found that there would be little effect because most of the wetlands were maintained by snowmelt and hillslope runoff rather than stream water (Ruddy and Williams, 1991). However a similar study conducted along Cross Creek in Colorado's Holy Cross Wilderness concluded that back-watering from the stream was critical for maintaining water levels in the adjacent subalpine wetlands. Diverting a portion of the streamflow would eliminate this back-watering effect, leading to substantially reduced wetland water levels (Rovey et al., 1986).

Depression wetlands are theoretically less likely to be affected by water diversions than riparian wetlands because they receive most of their inflows in the early summer when diversions have relatively little effect, and because outflow rates are relatively slow. In contrast, the steep topographic gradient across toeslope wetlands suggests that outflow rates are very rapid, making them extremely vulnerable to any reduction in inflows. However there have been virtually no hydrologic studies of depression or toeslope wetlands in the central Rocky Mountains. Given the increased pressure on water resources in the Rocky Mountains and the ecological importance of depression and toeslope wetlands there is an urgent need to understand their hydrology, so that the potential impacts of water diversions on these types of wetland can be assessed.

We conducted a two-year study (1997-1998) of the hydrology of a toeslope wetland complex in the Kawuneeche Valley on the west side of Rocky Mountain National Park, Colorado. The Kawuneeche Valley contains some of Colorado's largest subalpine wetland and riparian complexes, and is also the upper headwaters of the Colorado River (Figure 1). The valley is bordered by the Never Summer Mountains to the west and the Front Range to the east. Toeslope wetlands occur along the base of the 1000-meter high hillslopes that flank both sides of the valley. Most of these toeslope wetlands are concentrated around tributary stream alluvial fans, and many of them are fens (Dr. David Cooper, pers.comm., July 2001).

Streamflows in the Kawuneeche Valley are affected by a major water diversion structure, the Grand Ditch. This 24-kilometer diversion canal was constructed in the late 1800s to provide irrigation water for farms on the eastern side of the Continental Divide (McKnight, 1983). The Ditch intercepts the flow of eleven headwater tributaries of the Colorado River and diverts it across a low point on the Continental Divide (Figure 1). Although there is some interannual variability due to the timing of snowmelt, the Ditch usually operates from mid-May until September, and reduces streamflow and stage in the diverted tributaries and the Colorado River throughout the summer each year.

In the 1930s the Ditch was incorporated into Rocky Mountain National Park (RMNP), but the ditch owners maintained the right to divert water (McKnight, 1983). Resource managers at RMNP are concerned that the diversion has adversely affected park wetlands and riparian areas. A specific concern is that the diversion of tributary streamflow has reduced surface water and stream-fed groundwater inflows to toeslope wetlands, resulting in a decline in water levels during the summer months. A decline in water levels could result in a shift in species composition towards plants adapted to a deeper water table. In toeslope wetlands that are fens a decline in water levels could result in reduced peat accumulation rates, and even a shift from a peat-gaining to a peat-losing system (Chimner, 2000).

The objectives of our study were to: i) determine the hydrologic regime of the study wetland under the current hydrologic conditions; ii) estimate the wetland inflows that would occur in the absence of the Grand Ditch; and iii) determine the effect of the Grand Ditch on water levels in the toeslope wetland evaluated in this study. This study represents the first detailed description of the hydrology of an alluvial-fan toeslope wetland in the central Rocky Mountains. Thus it provides important information for land managers concerned with evaluating the hydrologic effects of water diversions on this type of wetland.

STUDY SITE

The study was conducted in an alluvial fan - toeslope wetland complex at Lost Creek, which is one of the tributary streams affected by the Grand Ditch (Figure 1). Lost Creek drains eastward from a cirque in the Never Summer Range, and is intercepted by the Grand Ditch at an elevation of 3100 m. Below the Ditch, Lost Creek flows in a steep bedrock gully for approximately 1 km. The creek then splits into two separate channels as it flows for another 150 meters across an alluvial fan at the foot of the hillslope (Figure 2). The fan is comprised of coarse alluvial sediment ranging from gravel to large boulders, and has an average slope of approximately 20%.

The north channel of Lost Creek flows directly to the Colorado River, while the south channel flows into a wetland complex at the eastern margin of the alluvial fan. This

1.5 ha wetland complex consists of a series of sloping terraces formed by the deposition of alluvial sediment and the accumulation of peat in abandoned beaver ponds. The dominant plant types in the wetland are willows (*Salix* spp.) and sedges (*Carex* spp.).

Water inputs to the wetland include precipitation, the south channel of Lost Creek, two springs at the toe of the alluvial fan (labeled as S_1 and S_2 on Figure 2), and groundwater. During wetter periods surface water leaves the wetland as sheet flow and via a series of small, anastomosing channels on the wetland surface. The other outflows from the wetland are groundwater flow and evapotranspiration.

The mean annual precipitation at the National Weather Service Grand Lake 1NW climate station, which lies 17 kilometers south of the study site (Figure 1), is 51.9 cm with a standard deviation of 9.8 cm. The period with lowest precipitation is typically from late May through mid-July. In late July and early August, monsoonal air flows cause convective thunderstorms.

Mean monthly temperatures at Grand Lake range from -7.9 °C in December to 16.1°C in July. Potential evapotranspiration (PET), calculated using the Thornthwaite method (Dunne and Leopold, 1978), ranges from 0 in the winter months to 7.7 cm in July. Mean monthly PET at Grand Lake exceeds the mean monthly precipitation by 1-2 cm in June, July, August and September.

METHODS

Weekly inflows to the Lost Creek wetland from mid-June to late September of 1997 and 1998 were calculated. Precipitation inflows were based on daily precipitation at the Grand Lake 1NW National Weather Service climate station. Snowpack data from the

Snotel stations at Phantom Valley and Lake Irene were used to compare the amount of runoff available from snowmelt in the two study years. The Phantom Valley station is 2.4 km southeast of the study site at 2752 m elevation and has a record from 1936 to the present. The Lake Irene station is 2.6 km east of the study site at 3261 m elevation and has a record from 1938 to the present (Figure 1).

Discharge in the south channel of Lost Creek was measured approximately weekly at three locations (Q_1, Q_2 and Q_3) that were 120 m, 60 m and 20 m, respectively, upstream from the wetland (Figure 2). The discharge at Q_3 represented surface water inflows to the wetland. Differences in discharge between the three stations were used to calculate gains or losses along the channel.

Flows at Q_1 and Q_2 were measured using 90-degree V-notch weirs constructed from plywood. Tin sheeting was used to create a sharp edge on the upstream edge of the V-notch. Seepage around the weirs was minimized by embedding the plywood 15-20 cm below the bed of the stream, and 25-30 cm into the banks on either side. Seepage immediately upstream from the weir was further minimized by laying plastic sheeting on the streambed for 2 meters upstream. Flow across each weir in liters per second (Q_{weir}) was calculated from the equation:

$$Q_{weir} = 430\ g^{0.5}\ H_{weir}^{\ 2.5} \qquad (1)$$

where H_{weir} is the head of water above the V-notch in meters and g is the gravitational constant in m/s^2 (Dingman, 1994).

In 1997 the flow at Q_3 was measured with a 7.5 cm cutthroat flume. Flow in liters per second (Q_{flume}) was calculated using the equation:

$$Q_{flume} = 27.2(3.281 H_{flume})^{1.72} \qquad (2)$$

where H_{flume} is the upstream gage height in meters (Dingman, 1994). In 1998 the flow at Q_3 was measured with a 12.5 cm cutthroat flume. Upstream gage height in the flume was converted to a flow value using rating curves from the manufacturer (Baski Inc., Denver, Colorado).

In early July 1998 a small dam was constructed to divert most of the flow in the north channel of Lost Creek into the south channel (Figure 2). Water was diverted from 11 July until 10 September, and this additional input of water allowed us to more rigorously evaluate the effects of sustained flow in the south channel on water levels and groundwater flow.

Flows at each of the two springs S_1 and S_2 were directed towards discrete outlet points using plastic sheeting and rocks. The flow at each outlet point was measured with a graduated cylinder and stopwatch. In early 1998 the outlet of S_2 was disturbed by the blowdown of a tree next to the spring. This caused the flow from S_2 to become more diffuse, and prevented it from being measured. Hence the discharge from S_2 in 1998 was calculated using a linear regression model that related the instantaneous discharge measured at S_2 in 1997 to the corresponding instantaneous discharge at Q_1.

Water levels in the wetland were measured in a network of eighteen monitoring wells (LC1 through LC18 on Figure 2). The monitoring wells were installed in June 1996 by hand auguring to depths of 90 to 145 cm. Each well was constructed from 2.5 cm diameter, hand-slotted PVC pipe. The hole around each well was backfilled with native soil.

Soil profile data were obtained from each of the well borings. Soil samples were collected from the upper 30 cm of the borings to aid classification of the soils. These samples were analyzed for grain size using the simplified hydrometer method (Gee and Bauder, 1986) and classified by texture in accordance with USDA (1994).

Vertical hydraulic gradients in the wetland were calculated from the water levels measured in piezometer nests installed adjacent to wells LC1, LC4, LC8, LC13, LC16, and LC17 (Figure 2). Each nest consisted of either two or three piezometers, designated sequentially from the shallowest (A) to the deepest (B or C). The piezometers were constructed from 1.5-cm diameter PVC pipe that was hand-driven to the desired depth. A steel T-bar was used to keep the piezometer straight and to prevent soil from getting inside the pipe.

Two additional piezometers (LC19 and LC20) were installed in September 1996 to measure the piezometric head near the toe of the alluvial fan. Due to the dense, cobbly sediments in the fan, these piezometers were constructed from 1.5-cm diameter steel well pipe, which was driven to a depth of approximately 120 cm using a sledge hammer.

Water levels in the wells and piezometers were measured approximately weekly, on the same day that surface water flows were measured. Groundwater fluxes into the wetland were calculated by substituting the measured vertical hydraulic gradients and hydraulic conductivity values into Darcy's Law (Freeze and Cherry, 1979). Hydraulic conductivity data were obtained from rising-head tests in monitoring wells LC1, LC2, LC9, LC10, LC12, LC14, LC15, LC16 and LC18 (Bouwer and Rice, 1976; Bouwer, 1989). Each test was repeated three times and the mean values were used in all calculations. The cross sectional area of groundwater flow represented by each piezometer nest was calculated by subdividing the total wetland area using the Thiessen polygon method (Dunne and Leopold, 1978).

RESULTS

PRECIPITATION

Winter precipitation in 1997 was higher than average. The 1 April snow water equivalents (SWEs) at Phantom Valley and Lake Irene were 26.9 cm and 74.5 cm respectively, which is about 15% above average. Summer precipitation was also above average. Although the June and July precipitation totals of 3.8 cm and 5.6 cm were close to their respective means, the August and September totals of 9.7 cm and 8.5 cm were almost twice the long term average. The longest period during the summer without rain was 14 days from 27 June to 10 July (Figure 3). Weekly precipitation from 19 June through 1 October 1997 ranged from 0.1 to 4.2 cm (Figure 4a).

Winter precipitation in 1998 was below average. The 1 April SWEs at Phantom Valley and Lake Irene were only 19.8 cm and 52.3 cm, which is 87% and 80% of average, respectively. Summer precipitation was generally above average, except in September. The June, July, and August precipitation totals of 4.8 cm, 8.6 cm and 7.3 cm were 20%, 60% and 30% above average, respectively. However the September total of 3.0 cm was 30% below average. The longest period during the summer without rain was 13 days from 23 June to 7 July (Figure 3). Weekly precipitation from 19 June through 1 October 1998 ranged from zero to 4.3 cm (Figure 4b).

SURFACE WATER INFLOWS

In 1997 the highest measured flow at Q_1 was 46 L/s on 25 June (Figure 5a). On 27 June the headgate on Lost Creek was closed, and by the next day the flow had dropped to 0.52 L/s. By 29 June the flow at Q_1 had dropped to 0.16 L/s, and by 2 July the flow at Q_1

ceased completely. Although the Grand Ditch ceased diverting water in mid-August, streamflow was not observed at Q_1 until mid-September, when the ditch operators diverted water from the Grand Ditch and into Lost Creek while they conducted maintenance work. This resulted in a flow of 3 L/s at Q_1 on 17 September, and a peak flow of 30 L/s on 22 September. By 29 September the flow at Q_1 had dropped back to zero.

In 1998 the flow at Q_1 prior to the start of the diversion was much less than in 1997. The highest flow recorded in late June 1998 was just 3.0 L/s (Figure 5b). Flow at Q_1 almost ceased after the ditch headgate was closed at the end of June. We began diverting water from the north channel of Lost Creek into the south channel on 11 July and this increased the flow in the south channel to nearly 8.0 L/s. Flow at Q_1 continued throughout July, August and September as a result of the diversion of water from the north channel. The lowest measured flow at Q_1 was 0.4 L/s in early September. As in 1997, water was temporarily diverted out of the Ditch and into Lost Creek in the fall while maintenance work was being performed. This resulted in a peak flow of 16 L/s on 23 October.

The measured flows at Q_2 and Q_3 were always less than the flows at Q_1 indicating that there was seepage from the channel into the alluvial fan sediments. Total seepage losses between Q_1 and Q_3 ranged from 0.59 L/s when the flow at Q_1 was 2.4 L/s, to 13 L/s when the flow at Q_1 was 46 L/s. In 1997 the flow at Q_3 peaked at 33 L/s on 25 June but dropped to zero by 28 June, only a day after the start of the diversion. There was no measured flow at Q_3, and hence no surface flow from Lost Creek to the wetland, until 22 September 1997, when the flow at Q_3 increased to almost 20 L/s. The weekly inflows to the wetland as determined from the flows measured at Q_3 ranged from 0 to 98 cm (Figure 4c).

In 1998 there was no flow at Q_3 between 26 June and 11 July as all of the flow from Q_1 was lost to seepage. However, the diversion of flow from the north channel on 11 July immediately resulted in a flow of 6.0 L/s at Q_3. Flow at Q_3 continued until 12 August, over a month later than in 1997. Weekly inflows to the wetland from the south channel of Lost Creek ranged from 0 to 25 cm (Figure 4d).

Linear regression showed that the flow rates at Q_1, Q_2 and Q_3 were closely related. Flows at Q_1, Q_2 and Q_3 were related by the equations:

$$Q_2 = 0.91Q_1 - 1.15\ (r^2 = 0.99, n=25, p<0.0001) \quad (3)$$

$$Q_3 = 0.83Q_2 + 0.07\ (r^2 = 0.96, n=15, p<0.0001) \quad (4)$$

where Q_1, Q_2 and Q_3 are in liters per second. The sample size for equation 4 was smaller than the sample size for equation 3 because there was no flow at Q_3 on ten occasions when discharge data were collected. The regression slopes for equations 3 and 4 were both significantly less than 1 ($p < 0.0001$ and $p = 0.0032$ respectively), indicating that seepage losses along the channel increased at higher flows. The intercept value in equation 3 was significantly different from 0 ($p<0.0001$), indicating that flows of 1.26 L/s or greater were required at Q_1 to maintain flow at Q_2. The intercept value for equation 4 was not significantly different from 0 ($p=0.8885$), indicating that at very low flows the seepage losses between Q_2 and Q_3 were within the range of error in the discharge measurements.

In 1997 the peak discharge of the two springs S_1 and S_2 at the toe of the alluvial fan occurred in late June at the same time as the peak streamflow in the south channel of Lost

Creek (Figure 5a). The peak discharge from S_1 was 0.77 L/s on 25 June, while the peak discharge from S_2 was 0.61 L/s on 24 June. After the diversion started on 27 June the flow from both springs rapidly decreased. Flow at S_2 ceased on 29 June, while the flow at S_1 ceased on 2 July. When streamflow resumed in the south channel on 21 September, both springs began to flow again within 24 hours. The combined weekly flows into the Lost Creek wetland from S_1 and S_2 ranged from 0 to 5.1 cm in 1997 (Figure 4e).

In 1998 the highest flow recorded at S_1 prior to the start of the diversion was only 0.11 L/sec, which was much lower than in 1997. However, flow at S_1 continued until 27 July, more than two weeks longer than in 1997 (Figure 5b), and only ceased after flow at Q_3 dropped below 3 L/s. Total weekly inflows to the wetland in 1998 ranged from 0 to 0.8 cm (Figure 4f). The close relationship between streamflow and spring seepage rates in both 1997 and 1998 indicates that the springs are maintained by seepage along the south channel of Lost Creek.

GROUNDWATER INFLOWS

The soil profiles in most of the well borings consisted of 1- 1.5 meters of interbedded clayey silt and sand, underlain by sandy gravel of unknown thickness. The soil samples collected from the 0 – 30 cm depth interval in fifteen of the well borings were classified as either silt loam or sandy loam (USDA, 1994). These sediments are alluvial deposits from Lost Creek and lacustrine deposits laid down in abandoned beaver ponds. In the southwest corner of the wetland, near wells LC4, LC5 and LC6, the upper 30-50 cm of the soil profile consisted of peat rather than mineral soils.

The hydraulic conductivity values calculated from the rising head tests ranged from 4.5×10^{-4} cm/s in LC1 to 2.7×10^{-3} cm/s in LC2, with a mean of 1.2×10^{-3} cm/s. Since all of the wells tested were screened primarily in fine grained mineral soils, these values are consistent with the observed textural characteristics (Freeze and Cherry, 1978). The small range in hydraulic conductivity values suggests that the soils in the upper part of the profile are generally similar in each of the wells tested. No hydraulic conductivity data were obtained for the peat horizon in the southwest part of the site. However, rising head tests conducted in two wells screened in a similar peat horizon elsewhere in the Kawuneeche Valley indicated hydraulic conductivity values of 1.9×10^{-4} cm/s and 3.5×10^{-4} cm/s, respectively (Woods, 2000).

Prior to the start of the diversion in late June 1997, the overall direction of groundwater flow was from the toe of the alluvial fan towards the Colorado River (Figure 6). Groundwater was observed exfiltrating at the surface at numerous points along the toe of the alluvial fan. The water levels in the two piezometers at the toe of the fan (LC19 and LC20) were almost a meter higher than the water level in the adjacent wetland and there were positive hydraulic gradients in the piezometer nests at LC8, LC16 and LC17 (Figures 7a and 7b), indicating that there was groundwater discharge into the wetland across approximately 20% of the total wetland area. On the basis of the hydraulic gradients shown in Figure 7, the measured hydraulic conductivity values, and a cross-sectional area of groundwater flow of approximately 3000 m^2, groundwater inflows in this area in the week prior to the start of the diversion were approximately 5.0 cm (Figure 4g).

In the southern and eastern parts of the wetland groundwater flow was primarily horizontal or downward. The upward gradient at piezometer nest LC4, was caused by the beaver dam immediately upstream, and did not indicate upward flow from deeper soil horizons. The relatively impermeable material in the beaver dam restricted horizontal groundwater flow, and this resulted in a hydraulic gradient between the upstream and downstream sides of the dam. The water level in the deep piezometer at LC4 reflected the higher head above the beaver dam. A negative hydraulic gradient at LC1 indicated that groundwater in the southeastern part of the wetland was flowing downward and presumably into the Colorado River.

After the ditch began operating on 27 June 1997, many of the groundwater seepage points at the toe of the fan stopped flowing. At the same time the water levels in LC19 and LC20 began to drop. Both piezometers went dry by 30 June, so the actual decline in head was greater than the measured decreases of 0.28 m and 0.51 m, respectively. The vertical hydraulic gradient at LC8 switched from upward to downward, the upward gradients at LC16 and LC17 decreased slightly, and the gradient at LC1 became even more strongly downward (Figure 7). Due to the decline in hydraulic gradients near the toe of the fan the total groundwater inflow to the wetland in the week following the start of the diversion was just 2.4 cm, less than half the total for the previous week (Figure 4g). This sharp decline in groundwater inflow concurrent with the measured decline in streamflow indicates that groundwater flow at the toe of the fan is maintained at least in part by seepage into the alluvial fan aquifer along the south channel of Lost Creek.

During the first half of July the hydraulic gradient at LC8 remained downward, and the upward gradient at LC16 gradually decreased. Due to the decline in the gradient at LC16 the weekly groundwater inflows dropped to 1.0 cm (Figure 4g). A slight increase in the upward gradient at LC16 occurred in the latter half of the month and followed a period of increased rainfall. As a result of this increase in hydraulic gradient the calculated groundwater inflow increased to 1.4 cm per week. However groundwater inflows declined during a relatively dry period in early August and ceased completely by mid-August (Figure 4g).

In the first week of September an upward hydraulic gradient was re-established at LC8, and this coincided with a period of increased rainfall. This increase in the gradient at LC8 resulted in an increase in the weekly groundwater inflow to almost 6 cm. The increases in groundwater inflows during wet periods in 1997, and the corresponding decline during dry periods suggests that summer rainfall is the primary source of aquifer recharge during periods when surface water inflows are eliminated by the Ditch.

Vertical gradients increased in the piezometers after streamflow was temporarily reestablished in Lost Creek in mid-September, and the weekly groundwater inflow increased to over 7 cm (Figure 4g). However, the hydraulic gradients decreased and inflows from groundwater dropped sharply again after Lost Creek went dry in late September. Once again, this close association between groundwater flow and streamflow suggests that stream seepage is a critical source of alluvial fan groundwater recharge.

In late June 1998, the vertical gradients in piezometers LC1, LC4 and LC8 and the overall groundwater flow direction were similar to those observed during the same period in 1997 (Figure 7c). However, well LC19 was dry and the water level in LC20 on

25 June 1998 was 43 cm lower than on the same date in 1997. The upward gradient in LC16 was smaller than in 1997, and there were downward gradients at LC13 and LC17 (Figure 6d). These lower hydraulic gradients were due to the smaller snowpack in 1998, which resulted in less recharge to the alluvial fan aquifer from direct infiltration of snowmelt and reduced seepage along the stream. Due to the fact that most of the hydraulic gradients were lower than in 1997 the estimated groundwater inflow for the week ending 25 June 1998 was 30% less than for the same week in 1997 (Figure 4h).

After the diversion started the water level in LC20 dropped below the bottom of the piezometer within 24 hours. This indicates that groundwater discharge from the fan had decreased even though there was still flow in the south channel of Lost Creek. In contrast with 1997, the vertical gradient in LC8 remained positive after the diversion started, and became even more positive in mid to late summer (Figure 6c). By mid-August the hydraulic gradient indicated by the piezometers at LC8 had become unrealistically high, and it was concluded that the lower piezometer had become blocked.

The hydraulic gradient at LC16 remained almost constant throughout July and August (Figure 6d), and was always higher than in 1997. Although Lost Creek went dry at the end of July, above average rainfall apparently helped maintain groundwater inflows during the latter part of July and throughout August. Groundwater inflows to the wetland eventually ceased in mid-September, a month later than in 1997 (Figures 4g and 4h). Since rainfall in August and September 1998 was less than in 1997 the implication is that continued seepage into the alluvial fan aquifer from the stream maintained groundwater flow until later in the summer.

WETLAND WATER LEVELS

Prior to the start of the diversion in late June 1997 water levels across most of the Lost Creek wetland were at or near the surface. On 19 June, for example, twelve of the eighteen wells had water levels above the ground surface, and four of the other six wells had water levels that were within 10 cm of the surface (Figure 7). These high water levels were a result of three inter-related factors. First, surface water from the south channel of Lost Creek created a water track that flowed east between wells LC15 and LC13 before splitting into two. One branch of the water track continued east towards LC17 and the other branch flowed south towards wells LC1 and LC2 (Figure 5). Wells within the water track were flooded as long as there was flow in Lost Creek. Second, some of the flow in the water track together with water from the two springs and groundwater discharging at the surface created ponds behind abandoned beaver dams, and this increased the flooded area. Third, groundwater discharge at the toe of the fan raised the water table level across the upper part of the wetland.

The decline in surface water and groundwater inflows that occurred after the start of the diversion in late June 1997 caused water levels throughout the wetland to drop. The decline was particularly rapid in the first 3 to 4 weeks after the diversion started. For the wetland as a whole, water level declines in the period from 25 June until 16 July 1997 ranged from 2 cm in LC4 to 77 cm in LC1, with a mean of 36 cm. Spatial variability in the magnitude of the water level decline was due primarily to differences in the relative importance of surface water and groundwater inflows.

The biggest water level declines were in the southeast corner of the wetland (wells LC1, LC2 and LC9), where flow in the water track had created a pond behind a beaver dam. Water levels in the three wells in this area dropped by 75 cm or more between 25 June and 16 July after the water track ceased to flow and the pond went dry (Figure 8a). Water levels in the northern part of the wetland also decreased, but did not drop as far as the water levels in the southeast corner. The biggest water level decreases in the northern part of the wetland were in areas that had been flooded by the water track (wells LC13, LC15 and LC17) where water levels dropped by approximately 40 cm between 25 June and 16 July (Figures 8b and 8c). Water levels around the edges of the water track (wells LC10, LC11, and LC12) dropped by 20 to 30 cm. These results illustrate the importance of the water track for maintaining water levels in this part of the wetland. Water levels probably did not drop as far here as in the southeast corner of the wetland because of the additional recharge provided by groundwater inflows and because surface water runoff was restricted by several abandoned beaver dams.

The smallest water level declines in early to mid July 1997 occurred in the southwest part of the wetland (wells LC3 through LC8), which consists of a series of small abandoned beaver ponds. The average water level decline in the six wells in this area between 25 June and 16 July was just 15 cm. Although water levels declined rapidly immediately after the diversion started, the rate of decline slowed considerably after just a few days. The smaller water level decline in this area was due to three factors. First, the proximity of this part of the wetland to the toe of the fan resulted in a greater amount of groundwater inflow. Second, the beaver dams in this area restricted surface water runoff. Third, water levels in the vicinity of wells LC3 and LC4 were supported by seepage under the beaver dam immediately upstream. The water level in well LC4 remained at the ground surface throughout the summer because of this seepage.

The lowest water levels in most of the wetland wells occurred in mid to late July, following the driest period of the summer (Figures 3 and 7). However, 4.5 cm of rain fell in the last 4 days of July followed by another 2.0 cm in the first week of August, and water levels increased. Between 16 July and 7 August the average water level in the wetland increased by 14 cm. The biggest increases were in the eastern part of the wetland (wells LC1, LC2, LC9, and LC18), where the water level increased by an average of 47 cm. This increase in water levels following a wet spell indicates that summer rainfall is an important water source during periods when the Ditch is diverting water from Lost Creek.

In contrast with the rest of the wetland, water levels in three wells in the southwestern part (LC6, LC7 and LC8) decreased throughout the latter half of July and the first week of August. This decline in water levels corresponded with an overall decline in groundwater inflows to the wetland (Figure 4g). The lack of a response to rainfall in these three wells compared to the other wells may reflect the fact that the upper part of the soil profile in this area is fibric peat rather than mineral soil. Storage changes in peat can occur due to swelling and shrinkage of the peat pore structure, with little or no corresponding change in the water table level (Schlotzhauer and Price, 1999).

Water levels throughout the wetland increased after flow in Lost Creek was re-established in mid-September 1997. The water track, which had been dry since the start of the diversion, started to flow again resulting in substantial increases in the water levels in the southeast corner and the northern part of the wetland. For example, the water level in well LC15 increased by 38 cm between 13 and 20 September (Figure 8b). During the period in September when Lost Creek was flowing water levels were similar to those recorded prior to the start of the diversion in late June. However, once the stream went dry water levels rapidly dropped again. This clearly indicates the importance of surface water and groundwater inflows for maintaining high water levels in the Lost Creek wetland.

In late June 1998 the water levels in sixteen of the eighteen wells in the Lost Creek wetland were lower than in the same period in 1997, and there was less standing water in the wetland. The biggest interannual differences were in wells LC1 and LC14, where the water levels on 25 June were 34 and 40 cm, respectively, lower than on the same date in 1997 (Figure 7a). Water levels in two wells in the southwest corner of the wetland were 1-2 cm higher (Figure 7e). The lower water level in most of the wetland in late June 1998 indicates that early summer water levels in the wetland vary from year to year depending on the size of the spring snowpack, primarily because the snowpack controls the amount of surface water runoff.

The diversion of Lost Creek started in late June 1998, but water levels in the wetland did not drop as rapidly as in 1997. Consequently, although late-June water levels were lower in 1998, mid-July water levels were generally higher. The mean water level in the eighteen wells on 16 July 1998 was –20 cm, compared to –38 cm on the same day in 1997. The first half of July 1998 had an additional 2.0 cm of rainfall compared to the same period in 1997, but the higher water levels in 1998 were due primarily to the additional surface water and groundwater inflows that resulted from our diversion of water from the north channel of Lost Creek..

After surface water inflows to the wetland from Lost Creek ceased at the end of July (Figure 4b), water levels in most of the wetland wells began to decline more quickly.

However, the rate of decline was slower than it was after surface water inflows ceased in early July 1997. The mean water table level in the eighteen wells declined just 11 cm in the three weeks following the end of surface water inflows in 1998 compared to a decline of 36 cm in the three weeks after the start of the diversion in late June 1997. The difference was largely due to the higher than average rainfall in August 1998. The first three weeks of August 1998 had 5.6 cm of rainfall, compared to just 0.2 cm in the first three weeks after surface water inflows ended in 1997.

The rate of water level decline increased considerably in many of the wells at the end of August. The average water level decline in the first week of September was 13 cm, compared to just 5 cm in the last week of August. This increase in the rate of water level declines corresponded to a much drier period, again indicating that precipitation played an important role in maintaining wetland water levels. Due to this late season decline in water levels the average water level in the eighteen wells in mid-September was 16 cm lower in 1998 than in 1997.

DISCUSSION

HYDROLOGY OF THE LOST CREEK WETLAND

Streamflow from Lost Creek contributed more than 90% of the inflows to the Lost Creek wetland whenever the Grand Ditch was not operating (Figure 3). The water track formed by inflows from Lost Creek was critically important for maintaining high water levels across much of the wetland in the early summer. Due to the high elevation, runoff from the Lost Creek watershed is controlled primarily by the annual cycle of snow accumulation in the winter and snow melt in the early summer. Thus, if the Grand Ditch did not divert water from Lost Creek, surface water inflows to the Lost Creek wetland would typically peak in mid to late June and then gradually decline, with the minimum flows occurring between mid-August and early September. This is in contrast to the current conditions, where surface water inflows from Lost Creek are eliminated for most of the summer each year. Under undisturbed conditions, the additional inflows from Lost Creek would maintain water levels at or near the surface in those parts of the wetland that lie in or adjacent to the water track.

A critical question concerning the hydrology of the Lost Creek wetland is whether surface water inflows would cease in the late summer even if the Grand Ditch did not divert Lost Creek. This would indicate that the current conditions in the late summer are representative of the undisturbed condition because the Ditch has no effect. However, if streamflows would normally continue throughout the summer, then the undisturbed late summer conditions in the wetland would be substantially different. The magnitude of late summer flows in Lost Creek can be estimated using published flow data for the Colorado River. The mean daily runoff of the Colorado River headwaters in mid-August is typically about 0.009 $m^3/s/km^2$ (USGS gage no. 09010500, Colorado River below Baker Gulch, 1954-2000). Thus, if it is assumed that low flows in Lost Creek are divided equally between the north and south channels, and if seepage losses are calculated using equations 3 and 4, inflows to the wetland would average about 6 L/s in mid-August. Lost Creek remained dry after the diversion ended in August 1997, despite the fact that the 1997 snowpack was well above average. However, this was probably due to the fact that the Grand Ditch captures a portion of the flow in Lost Creek even when the headgate is open. At low flows these losses represent most of the flow from the upper part of the watershed. Under undisturbed conditions, inflows to the Lost Creek wetland from Lost Creek would continue throughout the summer of most years.

Undiverted streams in the Kawuneeche Valley that have similar drainage areas to Lost Creek continue to flow in the late summer each year, adding weight to the conclusion that Lost Creek is a perennial stream. The evidence of beaver activity in the Lost Creek wetland, in the form of abandoned dams and ponds, is also consistent with perennial streamflow under undisturbed conditions. Beavers require a permanent, relatively constant water flow in order to maintain their ponds (Olsen et al., 1994). The current absence of beavers from the Lost Creek wetland may be due to the fact that Lost Creek ceases to flow for most of the summer each year due to the effect of the Grand Ditch.

Flow from the two springs and groundwater discharge at the base of the Lost Creek alluvial fan made up most of the rest of the wetland inflows in periods when the Ditch was not operating. These inflows came from an aquifer in the coarse sediments that form the Lost Creek alluvial fan. Spring flow rates and groundwater inflows to the wetland were closely related to streamflow, as were seepage losses along the south channel of Lost Creek. Therefore, although it is not possible to make a direct link, it seems clear that seepage from Lost Creek is the primary source of recharge to the alluvial-fan aquifer. Streams in the eastern Sierra Nevada also lost water to seepage in reaches located on alluvial fan sediments (Kondolf et al., 1987). Due to the steep topographic and hydraulic gradient, groundwater moves very rapidly from Lost Creek to the toe of the fan. Therefore any decline in streamflow results in an almost immediate decline in spring seepage and groundwater discharge.

If the flow in Lost Creek continued throughout the summer, inflows to the wetland from the two springs and from groundwater would also be maintained. Several parts of the Lost Creek wetland were clearly more dependent on these spring and groundwater inflows than on inflows from Lost Creek. In the southwest part of the wetland in particular, water level fluctuations were closely tied to groundwater inflows. This part of the wetland has peat soils, in contrast to the rest of the wetland which has mineral soils. Peat can only accumulate in areas where the soil profile is almost permanently saturated (Moore and Bellamy, 1974), and even a small drop in water levels can result in the loss of organic matter due to aerobic decomposition (Chimner, 2000). Under undisturbed conditions groundwater inflows to this part of the wetland would almost certainly maintain higher water levels than those that occur presently. Although water levels in this part of the wetland do not drop as far as those in other areas, the current, hydrologically disturbed conditions may be unsuitable for peat to accumulate. Over the long term these conditions could result in shrinkage of the peat body or even the total loss of peat soils from this part of the wetland.

In many parts of the Lost Creek wetland, surface water from Lost Creek and the two springs and groundwater that exfiltrated at the toe of the fan became ponded behind beaver dams, and this helped to maintain some of the highest water levels in the wetland in the mid summer. Beavers are therefore a critical part of the hydrology of this type of wetland. Beavers have been recognized as performing a critical role in maintaining the hydrologic conditions in other wetland environments (*cf* Naiman et al. 1986; Woo and Waddington, 1990; Lowry and Beschta, 1994).There are presently no active beaver colonies in or near the Lost Creek wetland, and the dams have clearly been abandoned.

While the absence of beaver cannot be directly attributed to the effects of the Grand Ditch, the lack of surface water inflows suggests that it is unlikely that beavers will reoccupy the site as long as the Ditch continues to operate. The existing beaver dams will deteriorate over time due to lack of maintenance, and this will lead to a further lowering of wetland water levels.

The field data presented here were collected over two years, 1997 and 1998. Inflows to the Lost Creek wetland in the early summer of 1997 were an order of magnitude greater than in 1998, and most of the difference was due to greater flow in Lost Creek. Wetland water levels in the early summer were correspondingly higher in 1997 than in 1998. This indicates that early summer water levels in the Lost Creek wetland vary from year to year depending on the amount of streamflow, which depends primarily on size of the snowpack. This variability would occur even if the Ditch was not present. Since 1997 had a very large snowpack and 1998 had a below average snowpack, the differences in early summer water levels in the two study years provides a reasonable representation of the range of variability in early summer water levels.

Summer rainfall in this part of the Rocky Mountains is also subject to extreme interannual variability due to the varying influence of monsoonal moisture patterns (Hauer et al., 1997). The mean precipitation total for 1 June – 31 August at Grand Lake has a coefficient of variation of 38%. The elimination of surface water inflows and the gradual decline in groundwater inflows caused by the Grand Ditch meant that by the mid to late summer of 1997 rainfall provided most of the inflows to the wetland, and water levels in many of the wells varied considerably between dry and wet periods. Rainfall in July 1997 was close to average, and water levels dropped considerably in many wetland wells. In contrast, August 1997 was exceptionally wet, and water levels in many wells increased. The implication is that in wet years like 1997 the impact of the Grand Ditch on wetland water levels is mitigated by the increased amount of rainfall. Conversely, in dry years wetland water levels would be expected to drop even further than they did in 1997. However, if the ditch did not divert flow from Lost Creek, inflows from precipitation in the mid to late summer would be relatively small in comparison to the combined inflows from surface water, spring seepage and groundwater. Therefore, under undisturbed conditions, summer rainfall would have relatively little effect on wetland water levels.

EFFECT OF THE GRAND DITCH ON OTHER TOESLOPE WETLANDS

The Colorado River headwaters includes several other toeslope wetlands that lie close to alluvial fans. While few of these toeslope wetlands are directly connected to streams, many are located in areas where groundwater discharges at the edge of a fan. Given the demonstrated importance of surface water seepage as a source of groundwater recharge at the Lost Creek site, wetlands supported by seepage-fed groundwater may be just as vulnerable to the effects of the Grand Ditch as those directly connected to streams.

In 1996, as part of our wider study of the hydrologic effects of the Grand Ditch, we began collecting water level data from three peatlands that lie adjacent to the much larger alluvial fan of Red Creek. Red Creek lies approximately 3.5 km south of Lost Creek and it is also diverted by the Grand Ditch. Streamflows in Red Creek at the valley floor are reduced by up to 60% during the summer because of the diversion (Woods, 2000). In 1996 and 1998 water levels in two of the three peatlands at Red Creek dropped well below the surface during dry spells in the summer. Saturated soils are essential for peat to accumulate because the anaerobic conditions limit organic matter decomposition (Moore and Bellamy, 1974; Mitsch and Gosselink, 1993). Therefore the presence of peat in the Red Creek wetlands is inconsistent with the observed drops in the water table. Our observations at Lost Creek suggest that the water level decreases at the Red Creek peatlands are at least partly due to the reduction in streamflow in Red Creek and the corresponding decline in groundwater discharge from the Red Creek alluvial fan. However, the difficulty of manipulating the flows in Red Creek means that we have been unable to rigorously prove this by a comparable flow manipulation experiment.

WETLAND RESTORATION

In order to restore the hydrologic regime of toeslope wetlands affected by the Grand Ditch it will be necessary to restore flows in some or all of the diverted tributary streams. However, it may not be necessary to restore all of the flows in order to maintain high water levels in the Lost Creek wetland. Even relatively small amounts of water released through the headgate on the Grand Ditch would maintain higher wetland water levels because this would maintain seepage to groundwater and the water track.

The highest surface water inflow produced by diverting the north channel of Lost Creek in 1998 was just 6 L/s, but this maintained considerably higher water levels in the wetland. Equations 3 and 4 indicate that in order to maintain a flow of 6 L/s at Q_3 there would need to be a flow of just over 9 L/s at Q_1. If we assume no seepage losses in the reach between the Ditch and Q_1, a constant flow of 9 L/s during all of June, July and August could be maintained by releasing just 0.3% of the mean annual yield of the Ditch into Lost Creek. Even in a very dry year, when the yields in June, July and August were a standard deviation below the mean, the total required would still be less than 1% of the total yield. Larger amounts of water would be required in streams that have a larger drainage area above the ditch. For example, the water diverted from Red Creek in 1996 represented about 12% of the total yield of the Ditch. However, at least a partial restoration of one or more toeslope wetland in the Colorado River headwaters could be attained without completely eliminating the diversion of water by the Grand Ditch.

CONCLUSIONS

Surface water from Lost Creek and from two springs, together with seepage fed groundwater and precipitation were the primary inflows to the Lost Creek wetland. Lost Creek provided more than 90% of these inflows, and maintained a water track across part of the wetland as long as the stream was flowing. Inflows from the springs and from groundwater were highly dependent on streamflow, indicating that seepage from Lost Creek is a primary source of recharge to a shallow aquifer in the alluvial fan. The direct and indirect dependence on streamflow for maintaining wetland water levels indicates that alluvial fan wetlands like the one at Lost Creek are hydrologically distinct from other types of toeslope wetland, which depend primarily on inflows from hillslope groundwater.

The Grand Ditch eliminates surface water inflows and reduces groundwater inflows to the Lost Creek wetland during most of the summer each year. Due to the steep topographic and hydraulic gradients across the wetland, any reduction in wetland inflows almost immediately results in a decline in wetland water levels. The magnitude of the decline in water levels varies from year to year, with the greatest impact in years with below average summer rainfall. In general, the biggest water level decreases are in areas where surface water flowing across the wetland surface is the primary inflow. Smaller water level decreases occur in areas where groundwater is the primary inflow, or where beaver dams impede surface water runoff. Since there are currently no beavers in the wetland, a deterioration of the old beaver dams will probably result in a further lowering of wetland water levels.

If the Grand Ditch did not divert Lost Creek, summer water levels in the Lost Creek wetland would be higher in most years than they are now. However, interannual differences in the size of the snowpack would still have a major effect on wetland water levels in the early summer. Restoration of water levels in the Lost Creek wetland could be achieved by releasing less than 1% of the total annual yield of the Grand Ditch.

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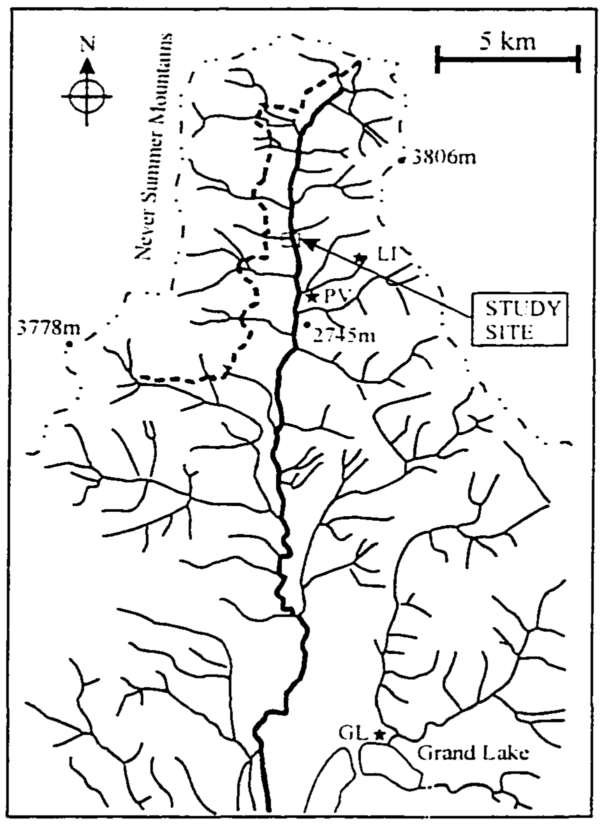

Figure 1. Map of Colorado River headwaters near Grand Lake, Colorado. The thick solid line is the main stem of the Colorado River, and the thinner solid lines are tributary streams. The dashed line is the Grand Ditch. Dot-dash line indicates the Continental Divide. Climate stations are indicated by solid stars: GL is Grand Lake 1NW, PV and LI are the Phantom Valley and Lake Irene Snotel sites, respectively.

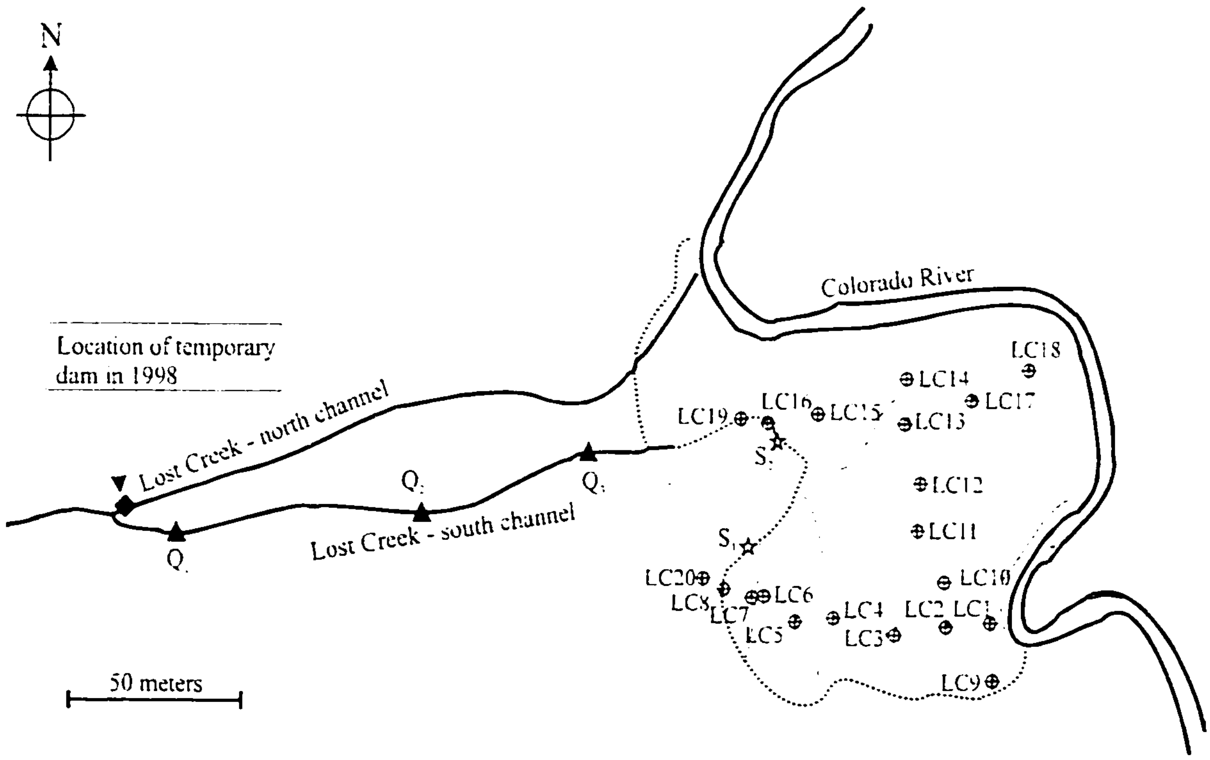

Figure 2. Map of the Lost Creek study site, showing locations of temporary stream gaging stations Q_1, Q_2 and Q_3 (solid triangles), springs S_1 and S_2 (open stars) and monitoring wells LC1 to LC20 (crossed circles). The dotted line indicates the wetland boundary, and the dashed lines indicate abandoned beaver dams.

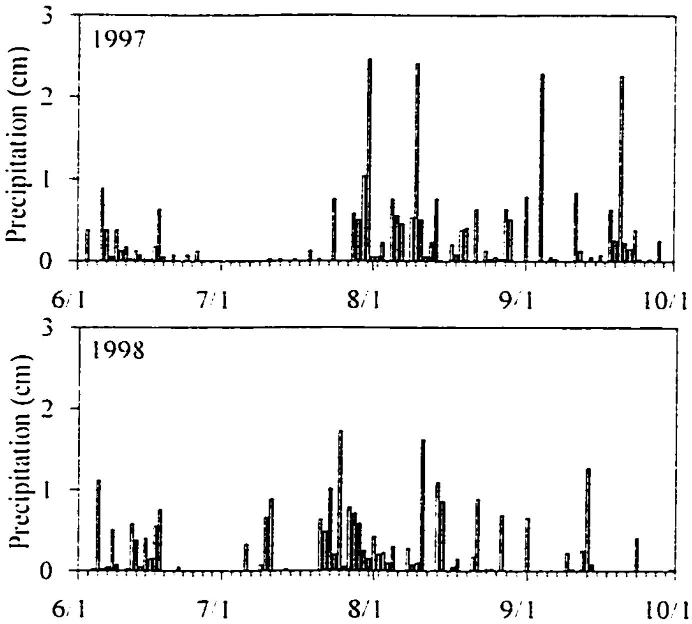

Figure 3. Daily precipitation at Grand Lake 1NW climate station between 1 June and 30 September for 1997 and 1998.

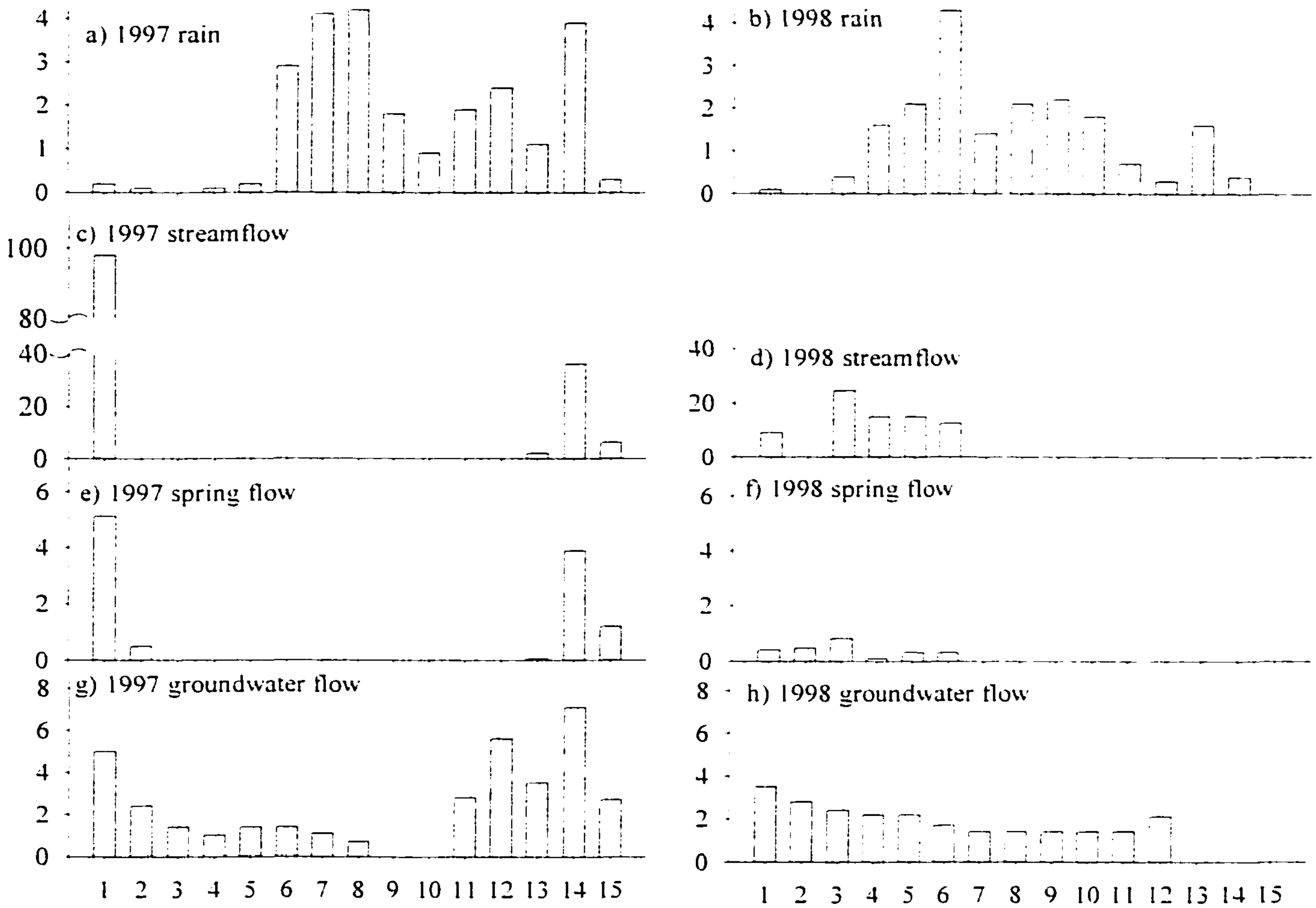

Figure 4. Weekly inflows to the Lost Creek wetland in 1997 and 1998 from precipitation (a and b), the south channel of Lost Creek (c and d), springs S_1 and S_2 (e and f) and groundwater (g and h). Weeks 1 through 15 begin 6/19, 6/26, 7/3, 7/10, 7/17, 7/24, 7/31, 8/7, 8/14, 8/21, 8/28, 9/4, 9/11, 9/18 and 9/26 respectively.

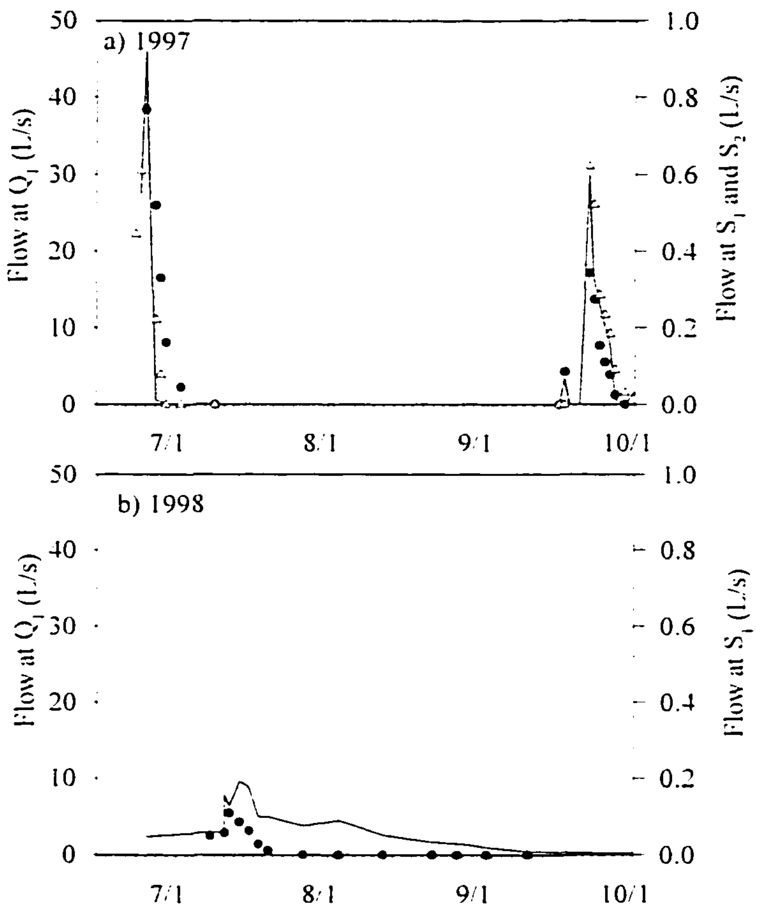

Figure 5. Flow in the south channel of Lost Creek at Q_1 (solid line) and at springs S_1 (solid circles) and S_2 (open triangles) in a)1997, and b)1998. There were no data for S_2 in 1998 because of damage to the weir.

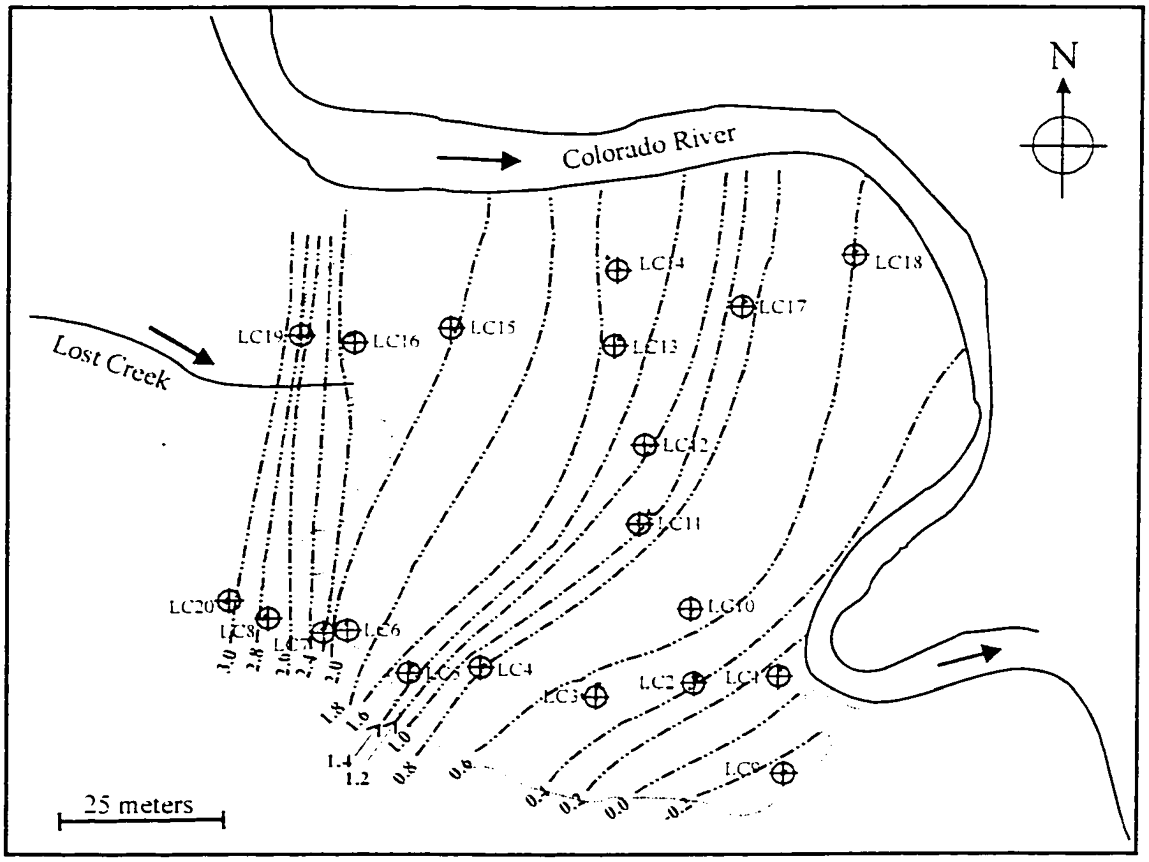

Figure 6. Water table elevations at the toe of the alluvial fan and in the Lost Creek wetland on 19 June 1997. Elevations are relative to a local datum. Dotted line indicates the wetland boundary.

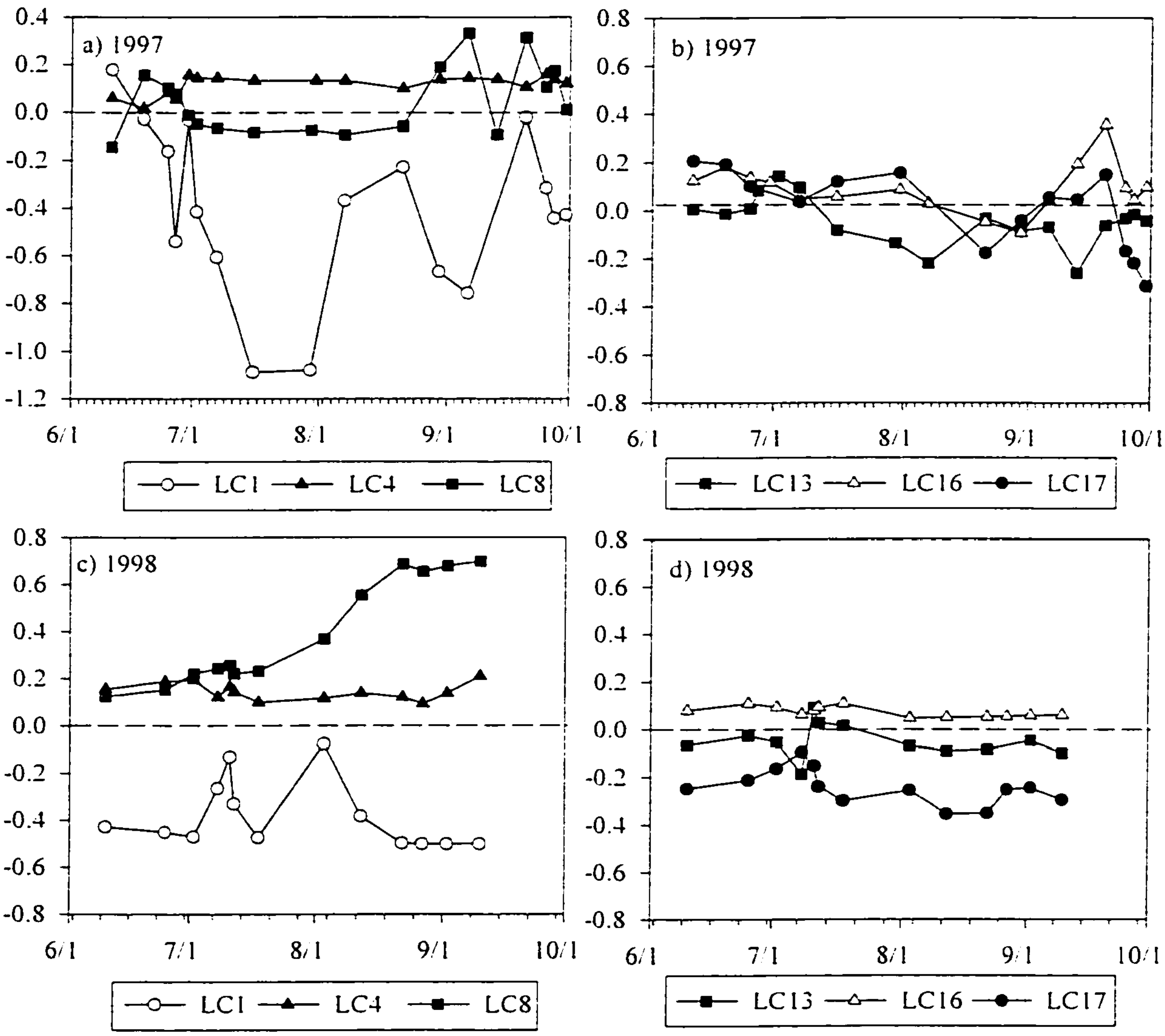

Figure 7. Vertical hydraulic gradients in the Lost Creek wetland in 1997 (a and b) and 1998 (c and d). The piezometer nests at LC8, LC4 and LC1 form a west to east transect across the southern part of the wetland, and the piezometer nests at LC16, LC13 and LC17 form a west to east transect across the northern part of the wetland. The gradients shown are between the deepest and the shallowest piezometer in each nest. Positive gradients are directed upwards.

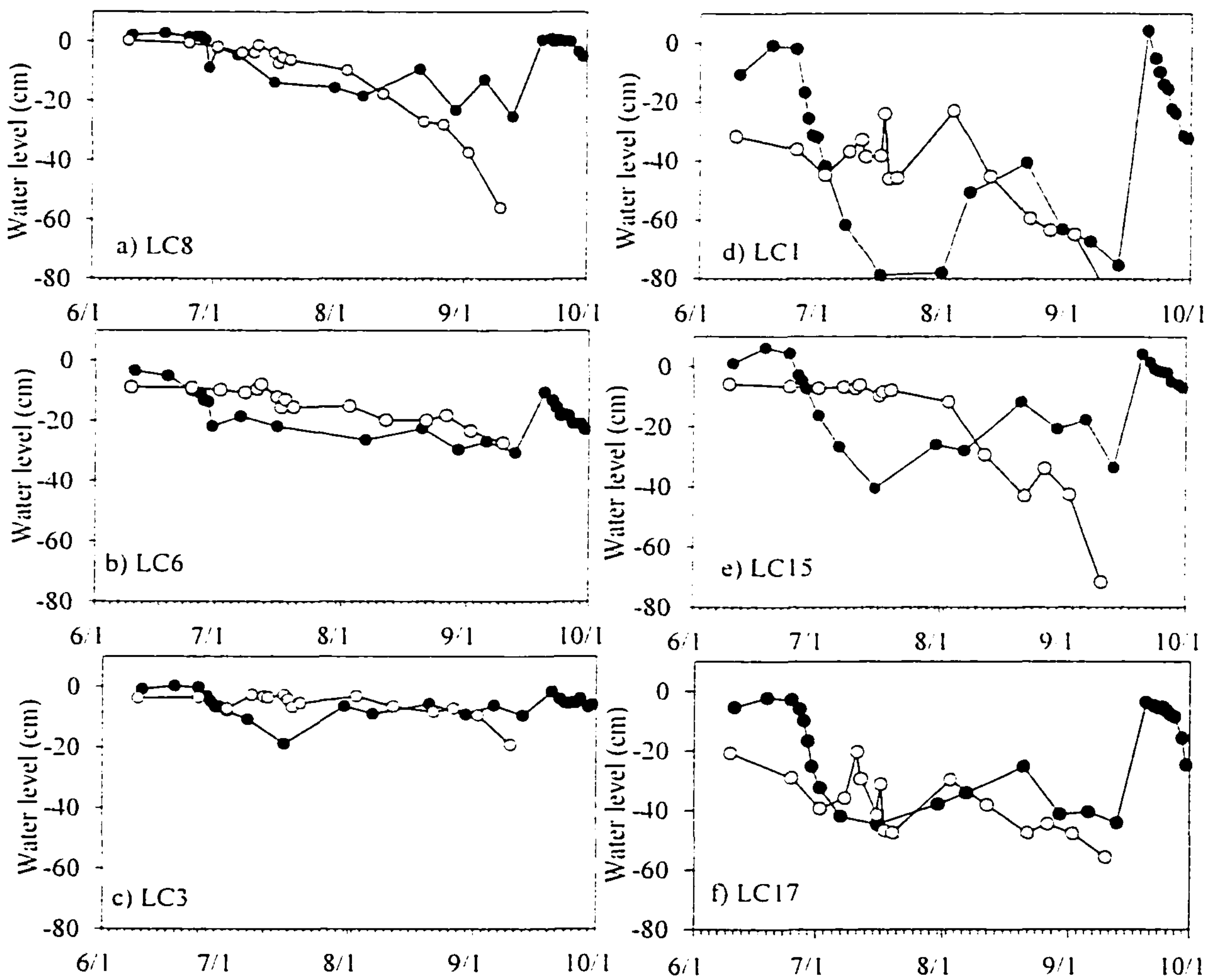

Figure 8. Water table levels in a) LC1, b) LC15, c) LC17, d) LC8, e) LC6 and f) LC3 in 1997 (solid circles) and 1998 (open circles). Wells LC1, LC3, LC6 and LC8 form a east to west transect across the southern part of the wetland. Wells LC15 and LC17 are in the northern part of the wetland.

5. SUMMARY AND CONCLUSIONS

This study addressed three concerns related to the effect of the Grand Ditch water diversion on subalpine wetlands in the Kawuneeche Valley in Rocky Mountain National Park. The concerns were that: 1) a reduction in the stage of the Colorado River is lowering the water table in riparian wetlands, 2) a lower riparian water table is limiting willow seedling establishment by reducing soil water availability, and 3) the diversion of tributary streams is lowering water levels in alluvial fan toeslope wetlands. The following sections summarize the results and conclusions related to each of these concerns.

EFFECT OF THE GRAND DITCH ON ALLUVIAL AQUIFER WATER TABLE LEVELS.

The effect of the Grand Ditch on water levels in riparian wetlands was investigated by installing 35 wells on the valley floor, and monitoring them approximately weekly during the summer in 1996, 1997 and 1998. Linear regression analyses indicated that the effect of Colorado River stage on water table levels decreased with distance from the river. Riparian water levels depended more on hillslope runoff than the Colorado River stage in confined valley sections. The Colorado River also had less effect on riparian water levels in wells near beaver ponds and oxbows. Thus, while the Colorado River is an important control on riparian water levels, there is considerable spatial variability in the strength of this relationship.

A numerical groundwater model was calibrated using the water level data from the wells, stage data from the Colorado River, and hydraulic conductivity data from falling head tests in 10 wells. Transient model simulations for the period between early June and late September in 1996, 1997 and 1998 indicated that the predominant direction of groundwater flow was down-valley. Hillslope groundwater discharge was typically less than 12% of the down-valley component of flow. There was a large and dynamic exchange of water between the alluvial aquifer and the Colorado River, with leakage into the alluvial aquifer ranging from 0.08 to 0.22 m^3/s, and discharge to the river ranging from 0.15 to 0.27 m^3/s. The net flux ranged from a gain of 0.2 m^3/s in June 1997 to a loss of 0.04 m^3/s in August 1996. Subsurface flow in the alluvial aquifer accounts for 4% to 50% of the total watershed runoff.

The modeled water table declines due to the diversion ranged from 0.01 m to 0.12 m. The maximum declines were in wells near the Colorado River in mid-July. Smaller declines were predicted earlier and later in the year, and in wells further from the river. Declines of 0.12 m or less are unlikely to adversely affect mature, deeply-rooted riparian trees and shrubs. However, the species composition of the shallow-rooted herbaceous understory may have changed.

These results indicate that stream-groundwater interactions along mountain stream valleys are highly spatially variable. The impacts of streamflow diversions on high-elevation riparian wetlands should therefore be evaluated on a site-by-site basis, with consideration given to factors such as valley width and the presence or absence of beaver ponds.

EFFECT OF THE GRAND DITCH ON WILLOW SEEDLING ESTABLISHMENT

The effect of the Grand Ditch on willow seedling establishment was investigated by conducting a split-split plot replicated experiment on three gravel bars along a 200-m subalpine reach of the Colorado River. The mean depth to the water table was significantly different between the low, intermediate and high elevation plots. Soil water content decreased with increasing depth to the water table. Consequently, the mean soil water content of the low elevation plots was significantly higher than in either intermediate or the high elevation plots with the same soil texture. Soil texture was also an important factor, as for a given elevation plots with medium sand soils had significantly higher soil water contents than plots with fine gravel soils. There was no significant difference in soil water content between watered and unwatered plots.

The number of willow seedlings at the end of the first growing season was positively correlated with mean soil water content, so the highest survival rates (12-24 seedlings per m^2) occurred in the low elevation plots with sand soils. No seedlings survived in plots that had a mean soil water content of <15%. This included all of the intermediate and high elevation gravel plots and several of the high elevation sand plots. During the spring peak flow of the following year all of the seedlings in the low and intermediate plots were killed by scouring. These results suggest that establishment is limited to areas that have sandy soils and are also protected from scouring flows until the plant develops a stronger root system.

The diversion reduced water table levels along the study reach by <1 cm to 15 cm during the 1999 growing season. The corresponding reduction in soil water content ranged from <4% in the high elevation sand plots to about 15% in the low elevation gravel plots. However, this decrease in soil water content had little effect on seedling survival rates. A potentially more serious impact of the diversion is the 50% reduction in the frequency of channel forming flows, which may be causing a decrease in the area of bare soils needed for seedling establishment.

EFFECT OF THE GRAND DITCH ON WATER LEVELS IN ALLUVIAL FAN TOESLOPE WETLANDS

The effect of the Grand Ditch on water levels in alluvial fan toeslope wetlands was investigated by calculating the weekly inflows to the Lost Creek alluvial fan toeslope wetland complex from mid-June to late September of 1997 and 1998. Surface water from Lost Creek provided more than 90% of the inflows to the Lost Creek wetland in the early summer. A series of three gauging stations along the alluvial fan showed that up to 25% of the flow in Lost Creek was being lost to seepage. Nested piezometers and monitoring wells confirmed that this seepage was the primary source of recharge to the alluvial fan aquifer. When flow in Lost Creek was suddenly stopped due to the diversion there was a rapid decline in groundwater gradients, a water level decline of up to 75 cm in some areas of the wetland, and a cessation of flows from springs at the lower margin of the alluvial fan. Conversely, the diversion of water into Lost Creek rapidly reversed these changes.

These results show that seepage from Lost Creek is critical for sustaining water levels in the alluvial fan aquifer, and this aquifer is critical for sustaining groundwater flow into the toeslope wetlands around the margin of the Lost Creek alluvial fan. The importance of streamflow as a source of wetland recharge means that alluvial fan toeslope wetlands are a hydrologically distinct type of toeslope wetland. The close connection between surface water and groundwater in alluvial fan toeslope wetlands means that streamflow diversions can adversely affect wetlands that are not immediately adjacent to the stream.

FUTURE RESEARCH

This study has addressed several key concerns related to the effects of water diversions on central Rocky Mountain wetlands, but it has also identified three key areas for future research. First, there is a need to determine whether the reduced geomorphic disturbance due to lower peak flows is adversely affecting riparian willow seedling establishment along diverted reaches of central Rocky Mountain streams. Along several sections of the Colorado River there is a vegetated low bank beneath a former cut bank, indicating that a new lower floodplain is being built in response to the smaller peak flows. In addition, several reaches of the Colorado River have stable mid-channel bars, and these indicate that the sediment supply of a stream is exceeding the transport capacity. These observations are consistent with a reduction in the peak flows of the Colorado River in the Kawuneeche Valley.

Ryan (1994) studied the effects of water diversions on the channel geometry of Colorado mountain streams, including the Upper Colorado River within Rocky Mountain National Park, and her observations were consistent with the present study. In some unconfined reaches the channel width had been reduced by 30-50% by vegetation encroachment on formerly active channel surfaces.

The expansion of riparian vegetation onto formerly active channel surfaces and the development of stable mid-channel bars may be just the first phase of a long-term change in riparian vegetation (Carter Johnson, 1998). If there is less scour and deposition and hence less establishment of willows from seed, this initial phase of adjustment may be followed by a decline in the willow shrublands that are the dominant riparian community in the Kawuneeche Valley.

The extent to which reduced peak flows along the Colorado River has resulted in a decline in willow recruitment depends on the relative importance of establishment from seed versus clonal regeneration. Relatively little is known about the reproduction of the willow species in the Kawuneeche Valley. Future work should focus on both long-term monitoring of riparian plant communities and studies of willow reproduction. Particular emphasis should be given to the role of geomorphic processes in both sexual and asexual reproduction in riparian willows.

A second research topic is the cause of declining beaver (*Castor canadensis*) populations in the Kawuneeche Valley and other central Rocky Mountain watersheds. Although beaver population data for the Kawuneeche Valley are limited, it appears that populations have declined over the last century (Dr. Bruce Baker, U.S.G.S., pers. comm, 1999). My hydrologic analyses indicated that water levels in the riparian wetlands along the Colorado River were often higher in areas near beaver ponds than in areas without ponds, suggesting that the ponds were sources of groundwater recharge. Abandoned beaver ponds were also important for maintaining higher water levels in the Lost Creek alluvial fan toeslope wetland complex. If there were more beaver in the valley, and hence more beaver ponds, groundwater levels would be increased in some areas and this could increase the area of wetland vegetation. An increase in the number of beaver ponds could also increase willow regeneration through the deposition of sediment in ponds and the subsequent creation of establishment sites as the ponds drain.

A third objective for future research is to further evaluate the connectivity between tributary streams on alluvial fans and toeslope wetlands around the fan margins. The study at Lost Creek demonstrated the importance of stream seepage for maintaining groundwater inflows to the Lost Creek wetland. Although the results are not presented in this dissertation I also monitored water levels in three peatlands adjacent to the much larger Red Creek alluvial fan. Red Creek is approximately 3.5 km south of Lost Creek and it is also diverted by the Grand Ditch. Streamflows in Red Creek at the valley floor are reduced by up to 60% during the summer because of the diversion (Woods, 2000).

In two out of three years water levels in two of the peatlands at Red Creek dropped well below the surface during summer dry spells. Saturated soils are essential for peat to accumulate because the anaerobic conditions limit organic matter decomposition (Moore and Bellamy, 1974; Mitsch and Gosselink, 1993). The presence of peat in the Red Creek wetlands is inconsistent with the observed drops in the water table. Both the results from the Lost Creek study and the monitoring at Red Creek suggest that the lower water levels in the Red Creek peatlands are at least partly due to the reduction in streamflow in Red Creek and the corresponding decline in groundwater discharge from the Red Creek alluvial fan. However, a stronger linkage might be documented by combining hydrometric data with chemical and isotopic comparisons of stream water, groundwater, and water in the peatlands around the Red Creek alluvial fan.

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