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Beaver dams and overbank floods influence groundwater–surface water interactions of a Rocky Mountain riparian area

Cherie J. Westbrook,[1,2] David J. Cooper,[1] and Bruce W. Baker[3]

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[1] Overbank flooding is recognized by hydrologists as a key process that drives hydrogeomorphic and ecological dynamics in mountain valleys. Beaver create dams that some ecologists have assumed may also drive riparian hydrologic processes, but empirical evidence is lacking. We examined the influence of two in-channel beaver dams and a 10 year flood event on surface inundation, groundwater levels, and flow patterns in a broad alluvial valley during the summers of 2002–2005. We studied a 1.5 km reach of the fourth-order Colorado River in Rocky Mountain National Park (RMNP), Colorado, USA. The beaver dams and ponds greatly enhanced the depth, extent, and duration of inundation associated with floods; they also elevate the water table during both high and low flows. Unlike previous studies we found the main effects of beaver on hydrologic processes occurred downstream of the dam rather than being confined to the near-pond area. Beaver dams on the Colorado River caused river water to move around them as surface runoff and groundwater seepage during both high- and low-flow periods. The beaver dams attenuated the expected water table decline in the drier summer months for 9 and 12 ha of the 58 ha study area. Thus we provide empirical evidence that beaver can influence hydrologic processes during the peak flow and low-flow periods on some streams, suggesting that beaver can create and maintain hydrologic regimes suitable for the formation and persistence of wetlands.

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1. Introduction

[2] Riparian areas are distinct from rivers and uplands. Riparian boundaries are often defined as extending outward from the stream bank to above the high water mark, which includes vegetation influenced by elevated water tables [*Gregory et al.*, 1991]. While these areas typically are noted for having seasonally saturated soils, they also can be relatively dry for extended periods of time. Complex interactions among river water, tributary streams, subsurface hillslope runoff, direct precipitation, and alluvial aquifers govern groundwater table dynamics in riparian areas [*Winter*, 1995; *Patten*, 1998; *Burt et al.*, 2002a, 2002b]. Groundwater levels often decrease over the summer months due to the combined effects of evapotranspiration by riparian vegetation, reduced inputs from adjacent hillslopes, and lower river stage. In mountain riparian areas of the western United States, groundwater levels may not recover until the following spring because snowmelt runoff provides the majority of annual streamflow and recharges hillslope aquifers. Understanding the mode of riparian area inundation and recharge of alluvial aquifers is critical for the management of river corridors and watersheds.

[3] Overbank flooding is a key hydrologic process affecting riparian water table dynamics and ecological processes such as biogeochemical cycling and plant diversity [*Naiman and Décamps*, 1997]. Overbank flooding typically occurs for a few days to weeks once every 1 to 2 years for most natural rivers [*Wolman and Leopold*, 1957]; this alternation of wet and dry phases enhances biotic diversity and productivity in the riparian area [*Junk et al.*, 1989]. River water can also be laterally transferred from the channel to the riparian area by infiltration into shallow alluvial aquifers, depending on the relative elevations of the river stage and groundwater tables [*Winter*, 1995; *Mertes*, 1997; *Chen and Chen*, 2003]. Riparian soil water and groundwater recharge can be greater during overbank flooding than from river-aquifer interactions or precipitation events [*Stanford and Ward*, 1988; *Workman and Serrano*, 1999; *Kingsford*, 2000; *Girard et al.*, 2003].

[4] Beaver (*Castor canadensis* Kuhl) may influence hydrologic processes in riparian areas of low-order rivers that can be dammed. Beaver dams raise river stage and can affect the exchange of water and sediment between rivers and adjacent riparian areas [*Woo and Waddington*, 1990; *Lowry and Beschta*, 1994; *Zav'yalov and Zueva*, 1998]. Where beaver dams span the entire valley the main hydrologic feature will be an upstream pond that elevates groundwater levels adjacent to the pond [*Naiman et al.*, 1988]. However, where valleys are unconfined yet rivers are narrow enough to be dammed by beaver the hydrologic

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[1] Department of Forest, Rangeland, and Watershed Stewardship and Graduate Degree Program in Ecology, Colorado State University, Fort Collins, Colorado, USA.

[2] Now at Department of Geography, University of Saskatchewan, Saskatoon, Saskatchewan, Canada.

[3] U.S. Geological Survey, Fort Collins, Colorado, USA.

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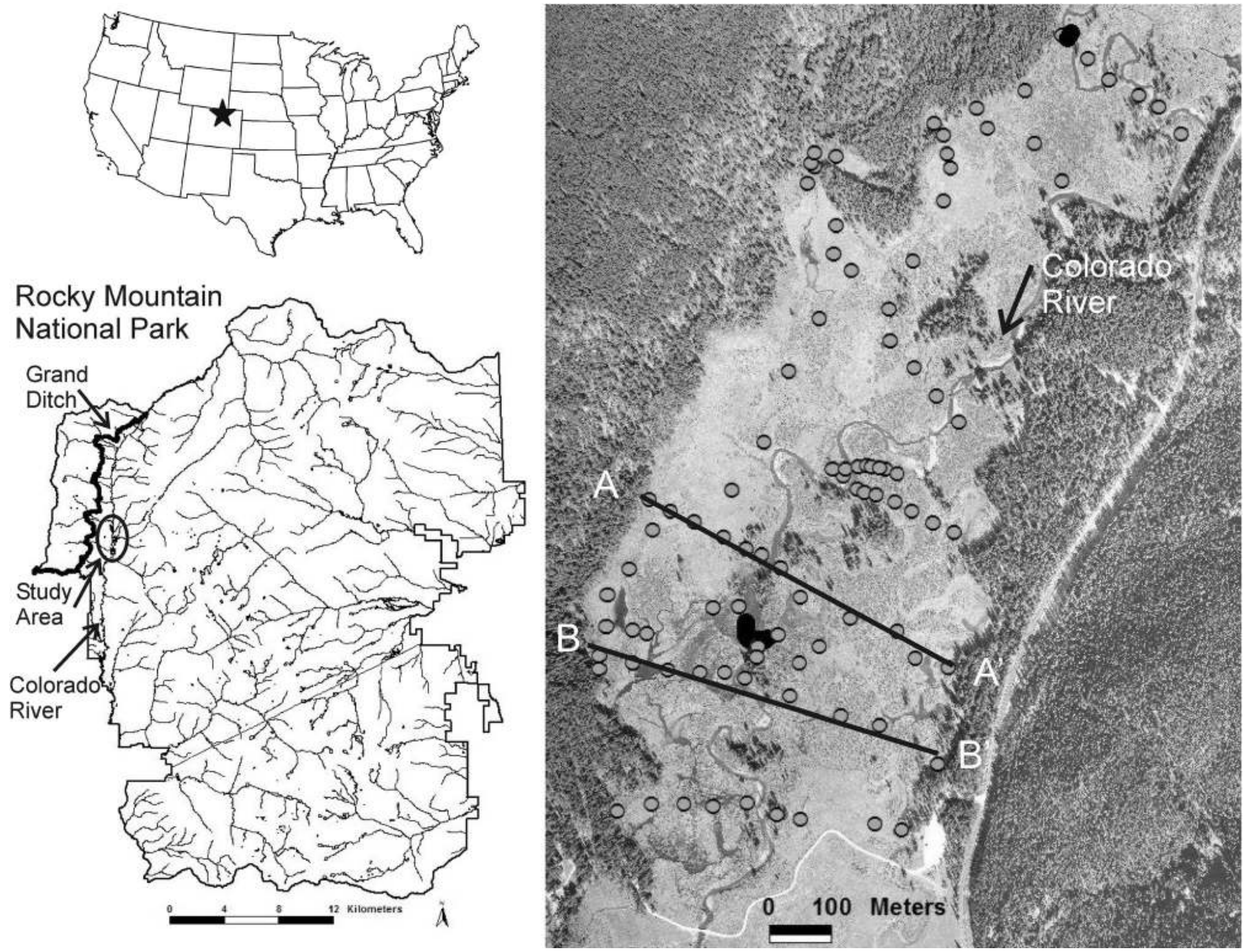


Figure 1. (left) Location of the general study area in Colorado and in Rocky Mountain National Park, Colorado, USA, and (right) a 1.5-km study reach of the upper Colorado River showing the location of 95 groundwater monitoring wells (circles) and the two beaver dams studied (irregular black spots). Cross sections A-A′ and B-B′ show the locations of groundwater wells used for Figure 5. The background aerial photograph was taken on 9 September 2001 and shows flooding at base flow caused by the lower beaver dam.

effects of beaver may extend far beyond the edge of the pond [*Lowry and Beschta*, 1994].

[5] The goal of this paper is to investigate the role of beaver dams and normal overbank flood flows on hydrologic processes in a montane riparian area. To do so, we examine patterns of surface inundation and groundwater flow, as well as groundwater levels dynamics in the valley containing the headwaters of the Colorado River in the central Rocky Mountains.

2. Methods

2.1. Study Site Description

[6] We studied a 1.5 km reach of the upper Colorado River in RMNP, Colorado, USA (40°22′N and 105°51′W). The site is a broad, high-gradient (0.01 m m^{-1}), alluvial valley with a mean elevation of 2720 m (Figure 1). The watershed area is 138 km^2 and ranges in elevation from 2667 to 3944 m. The floodplain lies at an average elevation of ~1 m above the channel bottom, is 0 to 25 m wide, and encompasses 1.5% of the 58 ha study area. The remainder of the valley is a terrace 0.7 to 1.2 m above the floodplain [*Woods*, 2001].

[7] The valley is bordered by two mountain ranges that each rise ~1200 m above the valley floor. The Front Range on the east side of the valley consists of Precambrian metamorphic rocks and the Never Summer Range on the west side consists of upper Oligocene granitic magmas covered by an extensive lateral moraine deposited during the Pleistocene glaciation [*Braddock and Cole*, 1990]. Several alluvial fans are present along the hillslope margins. Mineral soils in the valley average 0.9 m thick, have silt loam and loamy sand textures, and hydraulic conductivities of 1×10^{-6} m s^{-1} to 3×10^{-8} m s^{-1}, determined using both falling and rising head tests [*Fetter*, 2001]. Peat deposits of 0.3 to >1.5 m thick are present along the valley margins and have hydraulic conductivities of 2 to 4×10^{-6} m s^{-1}. Soils are underlain by 3 to 4 m of gravel alluvium that has a hydraulic conductivity of approximately 2×10^{-5} m s^{-1}. Below this gravel are 15–122 m

of Holocene and upper Pleistocene alluvium [*Braddock and Cole*, 1990] of unknown hydraulic conductivity.

[8] Mean annual precipitation within the watershed varies twofold along the elevation gradient, from 560 mm at a location 16 km downstream of the study site to 1130 mm near mountain tops. Runoff in the valley is derived primarily from snowmelt, with periodic summer thunderstorms in July and August. Mean annual precipitation is 640 mm with 42% falling as snow at the Phantom Valley SNOTEL station (CO05J04S, elevation 2750 m) and 885 mm with 84% falling as snow at the Lake Irene SNOTEL station (CO05J10S, elevation 3260 m). Mean annual potential evapotranspiration (using climate data from 1949–2003) in the valley is 430 mm, calculated using the Thornthwaite method [*Dunne and Leopold*, 1978]. Evapotranspiration exceeds precipitation for May to September. The long-term mean December and July air temperatures in the valley are −9.6°C and 12.4°C.

[9] The Colorado is a fourth-order, pool-riffle river that is 5 to 15 m wide in the study area. It is a meandering river and has a medium gradient (0.002 to 0.008 m m^{-1}). Streamflow is markedly seasonal, varying from 1.8 m^3 s^{-1} during the late summer base flow period to 14.7 m^3 s^{-1} at maximum discharge during snowmelt. Beaver built an L-shaped dam (lower dam) across the Colorado River on 24 August 1997 [*Woods*, 2001], which remained intact until breached by high streamflow on 29 May 2003. The lower dam was 1.7 m high, 30 m wide, extended 35 m upstream along the west side of the river channel, and consisted of willow and alder stems, mud, and river rocks. It diverted 70% of the Colorado River's flow onto the valley within a week of its completion [*Woods*, 2000]. Beaver used this diverted water to build a network of dams (∼6) and canals in the valley; these dams were 0.1 to 0.5 m high and 0.3 to 100 m wide. A second beaver dam (upper dam) was built across the Colorado River during early October 2003 and breached on 04 June 2005. The upper dam was 0.8 m high and 8.0 m wide and consisted of alder and willow stems.

[10] Vegetation in the valley is a mix of riparian shrublands dominated by *Salix monticola, S. geyeriana,* and *Betula fontinalis*, dry meadows dominated by *Deschampsia cespitosa* and *Calamagrostis canadensis*, and peat-accumulating fens dominated by *Salix planifolia* and *Carex aquatilis.* Hillslope vegetation is dominated by *Picea engelmannii* and *Abies lasiocarpa*. Plant nomenclature follows *Weber and Wittmann* [2001].

2.2. Precipitation and Colorado River Discharge

[11] Daily precipitation data were obtained from the Phantom Valley and Lake Irene SNOTEL stations; Colorado River discharge data were obtained from a U.S. Geological Survey (gauge 09010500) located 4.5 km downstream of the study site (elevation 2667 m). The watershed is also affected by the Grand Ditch, which has diverted 13 high-elevation tributaries out of the basin since ∼1890 and reduced the average annual flow in the Colorado River by 29% [*Woods*, 2001]. A log Pearson type III was used to estimate the annual flood distribution. We used recorded data for 1954 to 2003, which accounted for diversion that reduced peak flow in 38 of 50 years in the historical record. The U.S. Geological Survey estimated 2003 peak flow from a rating curve, as flows had overtopped the river banks; thus 2003 peak flow and our estimate of its recurrence interval are less accurate than for 2002 and 2004.

2.3. Flooding

[12] The extent of flooding by the 2003 peak flow and by the 2002 and 2004 main channel beaver dams in the valley were hand sketched on low-altitude (1:4000) aerial photographs that were printed at a scale of 1:700. Ground-based photographs and the location of flood debris and fresh sediment were used to assist in delineation of overbank flooding in 2003. The magnitude of floods required to produce overbank flooding similar to that achieved by the beaver dams were determined from a rating curve developed by *Woods* [2000] that correlated stream stage within the study reach to discharge at the U.S. Geological Survey stream gauge. The recurrence intervals of these floods were estimated using the flood frequency curve described above.

2.4. Groundwater Flow Patterns and Water Table Fluctuations

[13] We measured groundwater levels in 95 shallow monitoring wells situated in transects across the valley (Figure 1). Wells were constructed of 3.2 cm diameter, fully slotted PVC pipe, capped at the bottom, and installed with a hand auger to the base of the soil column. Five wells were installed at ∼1 m below the soil column at locations where the water table frequently dropped into the underlying gravel alluvium during the summer. These wells consisted of a 3.2 cm diameter steel drive point (0.9 m screen) connected to threaded and slotted 3.2 cm diameter PVC or steel pipe. The UTM coordinates and elevations of wells were surveyed using a Trimble 5800 GPS that was accurate to 0.5 cm in the horizontal dimension and 1.0 cm in the vertical. Depth to the water table was measured weekly at each well between May and September 2002, 2003, and 2004 using a small dial voltmeter connected to length-graded electric cable with two exposed wires that allowed an electric current to pass once they encountered water. Groundwater levels in well W24 were continuously monitored (25 May to 9 June 2005) before and after the upper beaver dam failure using a WL14 pressure transducer (Global Water Instrumentation Inc., California, USA). Contour plots of water table elevations and maximum depth to the water table were derived by kriging point observations in Surfer version 7 (Golden Software Ltd.). The average maximum depth to the water table was compared among years using a *t* test with a Bonferroni correction for multiple comparisons in SYSTAT version 10 (SPSS Inc.).

[14] Graphs of hydraulic head versus time for individual wells were used to evaluate the response of the unconfined valley groundwater system to the lower and upper beaver dams. Agglomerative cluster analysis of well data used Euclidean distance and average linkage grouping methods to identify wells with similar patterns and magnitudes of water table elevations over time [*Cooper et al.*, 1998]. Only data for June and July were used in this analysis as they represented the period when the water table drawdown was greatest. Data were standardized to the ground surface and cluster analysis was used to group wells by the shape and magnitude of their hydrographs via PC-ORD version 4.14 [*McCune and Mefford*, 1999]. Missing data were linearly

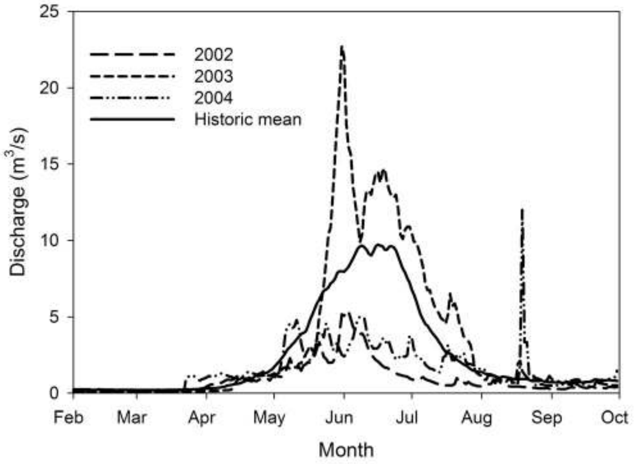


Figure 2. Colorado River mean daily discharge for 2002, 2003, 2004, and the historic mean (1954–2004). Recurrence interval estimates for the 2002, 2003, and 2004 maximum daily peak flows are 1.0, 9.6, and 1.6 years, respectively. The 2004 peak flow was caused by very severe thunderstorms 18–21 August.

interpolated if there were values before and after the missing value, otherwise the wells were excluded from the analysis. Wells were also excluded if the water table fell below the bottom of the well casing for extended periods of time; thus the analysis used 72 of the 95 wells. Clusters were plotted as a layer in ArcView and the mean hydrograph for each cluster was computed. Data were examined to determine which wells changed clusters among years. Wells whose water levels were more stable and had a greater magnitude when the lower beaver dam was intact (2002) than after it breached (2003) or when the upper beaver dam was intact (2004) than before it was constructed (2002 and 2003) were considered to be influenced by a beaver dam. All other wells were considered not influenced by a beaver dam.

3. Results

3.1. Precipitation and Stream Discharge

[15] Peak snow accumulation (as water equivalent) at the Phantom Valley SNOTEL station was 80%, 115%, and 58% of average in 2002, 2003, and 2004. At the higher elevation Lake Irene SNOTEL station, peak snow water accumulation was 58%, 103%, and 60% of average in these 3 years.

[16] Mean daily discharge of the Colorado River 4.5 km downstream of the study site was 0.8 $m^3 s^{-1}$ (range 0.2 to 5.4 $m^3 s^{-1}$) in 2002, 3.7 $m^3 s^{-1}$ (range 0.3 to 22.7 $m^3 s^{-1}$) in 2003, and 1.8 $m^3 s^{-1}$ (range 0.4 to 11.6 $m^3 s^{-1}$) in 2004 (Figure 2). Peak flow recurrence intervals were 1.0, 9.6, and 1.6 yr for 2002, 2003, and 2004. Both 2002 and 2004 had very low spring peak flows while 2003 had a peak flow that was approximately four times greater than in 2002 and was the fourth highest peak flow on record. The large peak flow in 2003 was due to high early summer temperatures that triggered rapid melt of an above average snowpack in the watershed above tree line. The peak flow in August of 2004 was the result of an especially severe thunderstorm and was the only annual peak flow recorded that was not driven by snowmelt.

3.2. Flooding

[17] In 2002, Colorado River water flowed from the 0.1 ha lower beaver pond obliquely across the western side of the valley, extending beyond the floodplain edge and onto the terrace (Figure 3a). Approximately 15% of the study area (8.7 ha) adjacent to and downstream of the dam was inundated for the month following peak flow. A flood with a recurrence interval of >200 years would be needed to achieve a stream stage similar to that produced by the 1.7 m height of this beaver dam. The area flooded by the lower dam contracted as the Colorado River dropped to base flow conditions in August when the river stage dropped below the western portion of the dam. Figure 1 identified areas that remained inundated through September 2002 as they were also inundated on 9 September 2001 when the valley was aerially photographed. Water that spread from the lower dam onto the terrace and floodplain returned to the Colorado River in eight separate locations, 70 to 500 m downstream of the dam.

[18] In 2003, overbank flooding during peak streamflow inundated 10% of the study area (5.8 ha), but the incursion of river water onto the valley was confined to a narrow zone adjacent to the river channel on the 2 year floodplain, neighboring low-lying areas, and oxbows (Figure 3b). Duration of the flooding in 2003 was much less than in 2002, and persisted for only 3 to 7 days. Flooding was also spatially variable as bank height varied greatly in the study reach.

[19] The upper beaver dam was present throughout the 2004 field season, creating a 0.2 ha pond, and like the lower dam diverted most of the Colorado River flow onto the valley floor (Figure 3c). Inundation of 21% (12.0 ha) of the study area persisted throughout the summer because beaver did not increase the effective bank height by extending the dam upstream. A flood with a recurrence interval of at least 20 years would be needed to achieve a stream stage similar to the 0.8 m height of the upper beaver dam. River water flowed from the pond southward down and across the valley and returned to the Colorado River in ten canals and channels located 350 to 930 m downstream of the dam. Beaver actively maintained some canals on the terrace, while some channels were in topographic lows formed by other processes.

3.3. Groundwater Flow Patterns and Water Table Fluctuations

[20] The equipotential lines on the flow nets were bent nearly parallel with the river channel in a localized area west of the lower dam (5.0 m isoline) during the high- and low-flow periods in 2002 (Figures 4a and 4d). Thus groundwater flow was directed from the river channel west across the valley when the lower dam was present. In contrast, in 2003 following the breach of the lower dam the horizontal flow direction was primarily down valley during high and low flow (Figures 4b and 4e). The upper dam did not alter the direction of groundwater flow in 2004 but did cause a steepening of the down-valley groundwater flow gradient from 1.2 to 1.9% during both high- and low-flow periods (Figures 4c and 4f).

[21] In 2002, the groundwater surface was elevated during both high- and low-flow periods along the A-A′

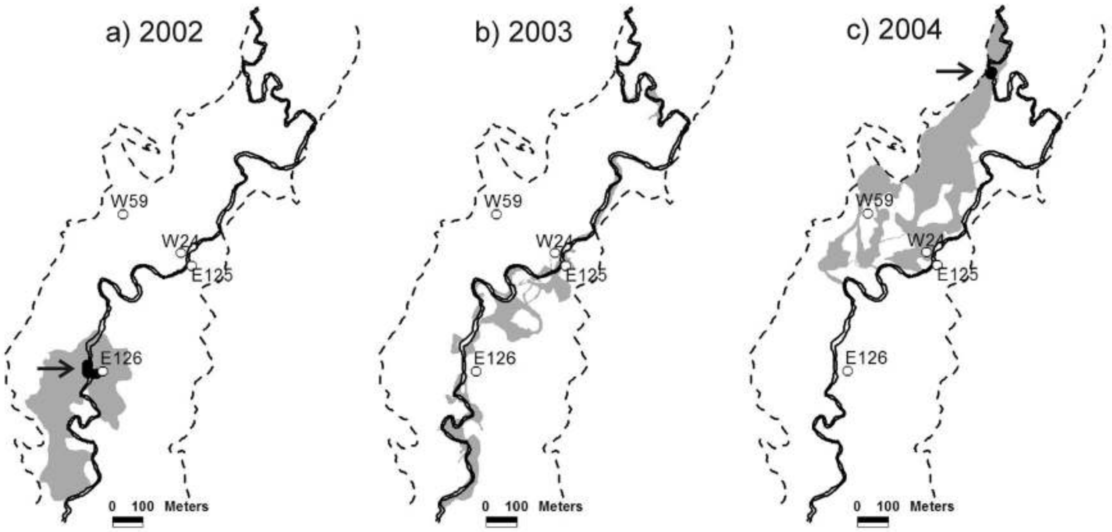


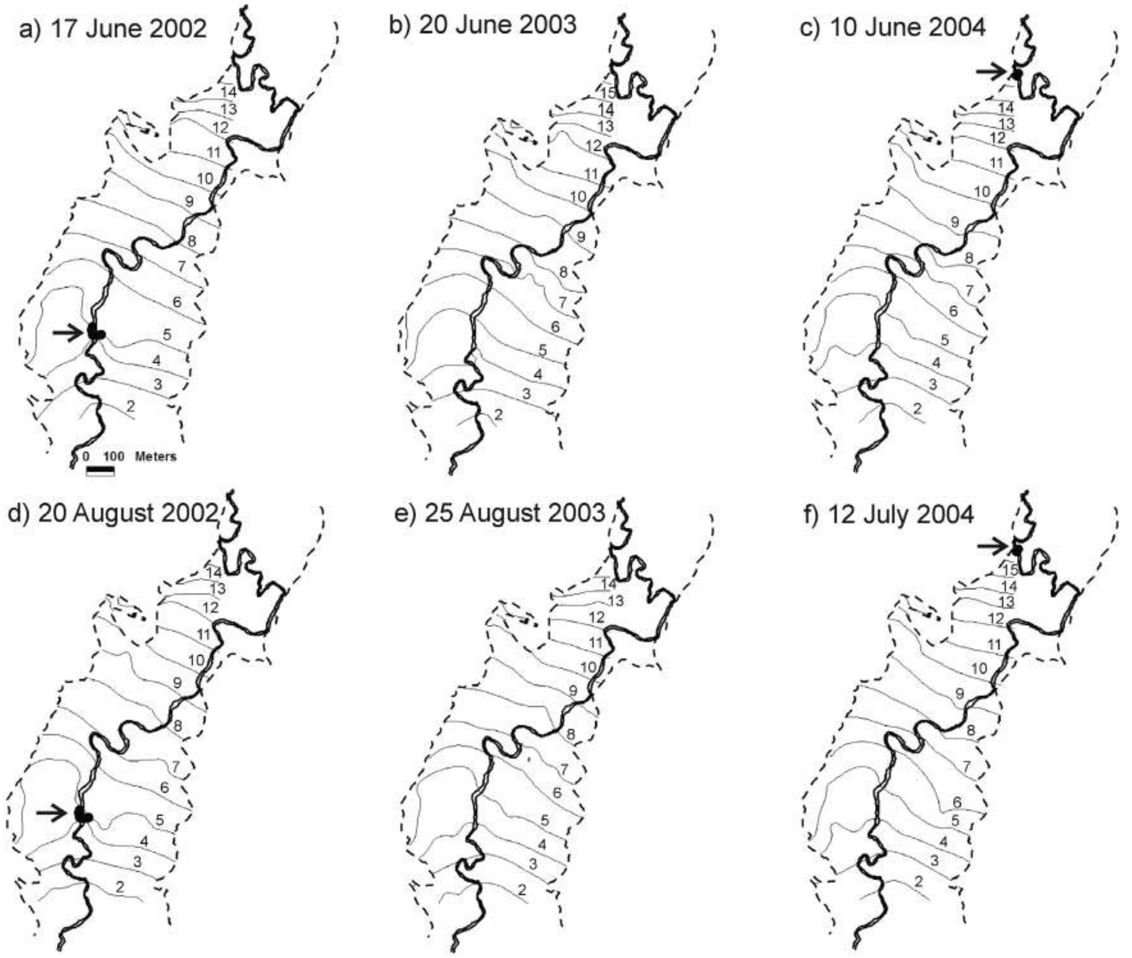
Figure 3. The 1.5 km study reach of the upper Colorado River valley showing maximum flooding (shaded) due to (a) the lower beaver dam (arrow points to dam) present in 2002, (b) the 2003 peak discharge, and (c) the upper beaver dam (arrow points to dam) present in 2004. The dotted line delineates the valley bottom, and the solid lines delineate the Colorado River. Note how flooding occurred only along the narrow riparian corridor in 2003 (high peak discharge year and no beaver dams) but occurred across large areas of the valley in 2002 and 2004 (low peak discharge years and beaver dams present). Individual hydrographs of three wells (E126, E125, and W59) are presented in Figure 7, and a continuous hydrograph of well W24 for the week before and after the breach of the upper beaver dam in 2005 is presented in Figure 8.

transect, located ~100 m upstream of the lower dam (Figures 5a and 5b). A nearly flat groundwater surface extended laterally for about 80 m east and 12 m west of the pond where there were abrupt changes in the hydraulic gradient, particularly west of the pond. In 2003, groundwater flow was toward the river following the snowmelt period (20 June, Figure 5a) and away from the river in late summer (10 August, Figure 5b). In 2004, the groundwater flow gradient was away from the river during June and August (Figures 5a and 5b), and during the rest of the year (data not shown).

[22] In 2002, groundwater levels near the stream channel remained stable and within 0.30 m of the ground surface along transect B-B′, which was located ~120 m downstream of the lower dam (Figures 5c and 5d). Water levels remained near or above the soil surface in the middle portion of the valley both east and west of the river during mid and late summer. Water flowed from the middle of the valley in opposite directions toward the eastern hillslope and the Colorado River downstream of the lower beaver dam, which indicated the presence of a groundwater mound in the middle of the valley. Water table elevation patterns were similar in 2003 and 2004, although water levels were consistently lower in 2004 when there was a shallower snowpack. The June water table was nearly level along transect B-B′ during both 2003 (Figure 5c), when the lower beaver dam was absent. By the second week of August in 2003 and 2004 (Figure 5d) a valley-wide decline in water levels had occurred.

[23] Three distinct types of well hydrographs were identified using agglomerative cluster analysis (Figure 6). Cluster 1 had water levels that changed little during the summer and they were near the soil surface. Cluster 2 wells had water levels ~30 cm below the ground surface in spring and declined an additional ~35 cm during the summer. Cluster 3 wells had water levels ~80 cm below the soil surface in spring and declined an additional ~35 cm or more during the summer. Water levels in several cluster 3 wells fell below the bottom of the well casing by late July in each year and could not be measured. Most wells were in clusters 2 and 3 during the dry years of 2002 and 2004; the only wells in cluster 1 were located in the area flooded by the lower beaver dam (2002), upper beaver dam (2004) or along the hillslope margins where groundwater discharge occurred. All but five wells fell into clusters 1 and 2 in 2003. There were 9 wells within the area flooded by the lower beaver dam that had higher and more stable groundwater levels in 2002 than in 2003 or 2004 even though 2003 was a much wetter year. Similarly, there were 12 wells within the area flooded by the upper beaver dam that had higher and more stable groundwater levels in 2004 than in 2003 or 2002.

[24] Fluctuations in water table elevations at wells E126, E125, and W59 were representative of seasonal variation in shallow groundwater of areas affected by the beaver dams or by overbank flooding during the study period (Figure 7). The highest groundwater levels in all wells occurred following peak flow in late May and early June. The water level in well E126, which was located 20 m east of the lower beaver pond, remained stable and within 10 cm of the soil surface throughout the summer of 2002. However, the water level in this well declined by ~60 cm in 2003 when the lower dam was absent and water levels were approximately 40 cm lower throughout 2004 than in 2003. Well E125 was affected by neither beaver dam in 2002 and 2004, but overbank flooding occurred within 10 m of the well during 2003; the water table was below the bottom of the


a) 17 June 2002

b) 20 June 2003

c) 10 June 2004

d) 20 August 2002

e) 25 August 2003

f) 12 July 2004

Figure 4. Groundwater flow patterns (isolines) for the Colorado River valley derived by kriging well point data, showing spring peak flow and low flow with (2002 and 2004) and without (2003) the presence of beaver dams (arrows point to dams). Isolines (1 m contours) are meters above an arbitrary datum and show that gradient for groundwater flow was mainly down the valley in absence of beaver or when the upper beaver dam (2004) was parallel to down-valley flow. The lower beaver dam (2002) was perpendicular to down-valley flow, and the 5 m isoline west of the dam shows the flow gradient is away from the river.

well throughout the 2002 and 2004 summers. Water levels in well E125 were within 10 cm of the surface during 2003 peak flow and declined to levels below the soil column by the end of July. The water table drawdown in well W59 was greater in 2002 than in 2003 likely because 2002 had a shallower snowpack and lower stream flow. In 2004 the ground surface near well W59 was flooded by the upper dam, which caused the water levels in well W59 to be higher than in 2002 and 2003 during periods of low streamflow.

[25] The failure of the upper beaver dam on 4 June 2005 resulted in a rapid decline in groundwater levels throughout the area inundated. Continuous measurements of water levels were available for well W24, which was located 670 m downstream of the upper beaver dam (Figure 8). Water levels in well W24 had a distinct diurnal fluctuation corresponding to the typical daily pulses in flow observed during snowmelt in the Colorado River (Figure 8) in the week preceding the upper dam failure. There was a rapid response of the water table 670 m downstream on the upper dam when it failed, although there was no coincident change in Colorado River discharge. The water table declined approximately 8 cm in 14 hours. While there were no continuous groundwater level measurements made for the well beside the dam, weekly data showed a decline in water levels from 21 cm above the ground surface three days before the failure to 41 cm below the ground surface seven days after the failure.

[26] The date when the water table was deepest for the 95 wells in the study area occurred later in 2002 (27 August) than in 2003 (10 August) or 2004 (12 July), which indicates snowpack size and at some wells, rain events are an important factor affecting the amount of groundwater storage. Average maximum water table depth was similar in 2002 and 2003 (63 versus 70 cm, *t* test: $P = 0.556$). The average maximum depth of the water table was 50 cm in 2004, which was significantly shallower than in 2002 ($P < 0.001$) and 2003 ($P = 0.037$). The mean drawdown, computed as the maximum minus the minimum water table, was 33 cm in 2002, 51 cm in 2003 and 26 cm in 2004, which

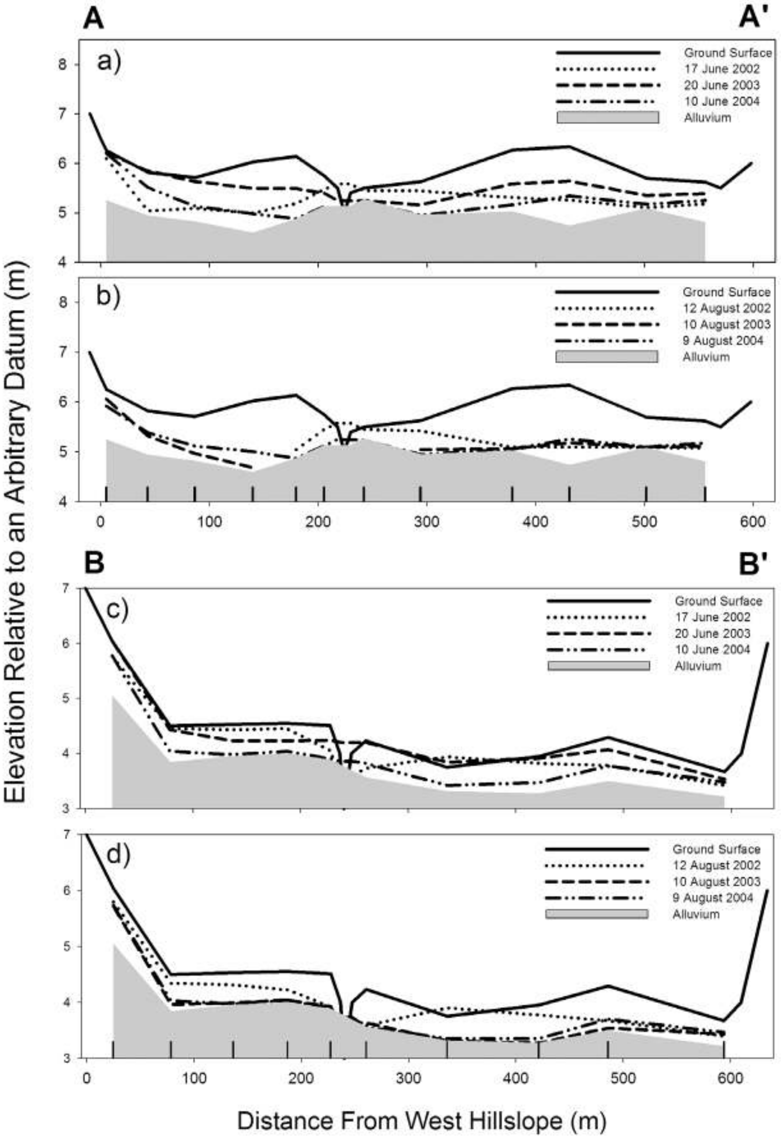


Figure 5. Groundwater levels following snowmelt (June) and during late summer (August) for (a, b) upstream cross section A-A′ (~100 m upstream of the lower dam) and (c, d) downstream cross section B-B′ (~120 m downstream of the lower dam). Vertical bars on Figures 5b and 5d denote the location of groundwater wells used to estimate water levels along each valley-wide transect. Horizontal groundwater flow was away from the river in the A-A′ transect, and groundwater levels remained near the ground surface in the middle of the valley in the B-B′ transect when the lower beaver dam was present in 2002 but not in 2003 or 2004.

reflected both the effects of beaver in the valley in attenuating the water table drawdown and differences in the relative amount of snow water equivalent. The maximum water table depth was within 40 cm of the ground surface in 47% (27.0 ha) of the study area in 2002, 31% (18.0 ha) in 2003, and 62% (35.9 ha) in 2004. The areas with the highest maximum water table depths in 2002 were adjacent to and downstream of the lower dam. This was because lower dam raised the stage of the Colorado River 1.7 m, which caused river water to spill out of the channel, spread laterally, and flow down valley. Areas with the shallowest maximum water table depths in 2003 occurred at the base of hillslopes where perennial groundwater springs supported peat soil development. The areas with the highest maximum water table depths in 2004 were downstream of the upper dam and along the base of the western hillslope.

4. Discussion

[27] Beaver strongly affected hydrologic processes of the Colorado River, its floodplain and terrace near its headwaters in the Rocky Mountains. Beaver dams and ponds greatly enhanced the depth, extent, and duration of inundation associated with floods. In-channel beaver dams created the hydraulic head necessary to raise water above the river banks and move it around dams as surface and groundwater flow during both high- and low-flow periods, spreading river water laterally and downstream of the dams. Each

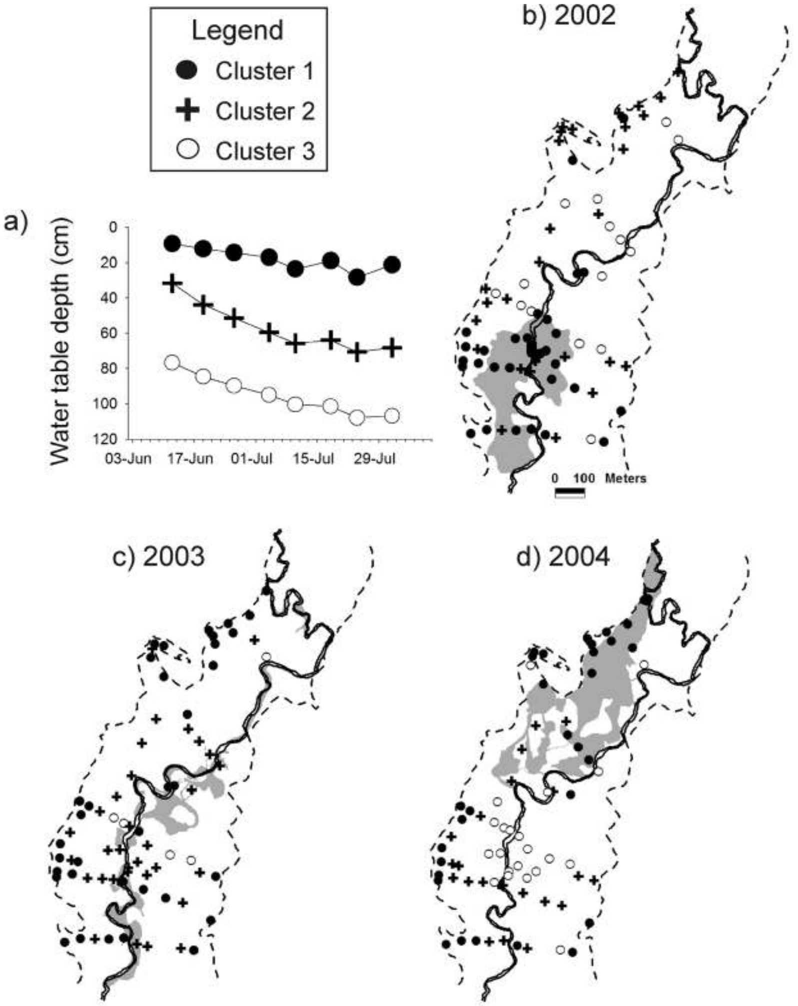


Figure 6. (b–d) Maps showing the results of the cluster analysis (refer to section 2 for analysis details) during the water table drawdown period, illustrating how beaver dams controlled groundwater levels in 72 wells. (a) Mean hydrograph of all wells in each cluster. The shading shows extent of flooding attributed to the lower beaver dam in 2002 (irregular black spot), peak streamflow in 2003, and the upper beaver dam in 2004 (irregular black spot).

beaver dam attenuated the water table decline in the drier summer months over roughly one quarter of the 58 ha study area that was mainly on the terrace. Our results suggest that beaver, through building dams, can influence hydrologic processes of some mountain valleys at large spatial and temporal scales, which can expand riparian expression.

4.1. Flooding

[28] Overbank flood events have generally been regarded as the main hydrologic mechanism for replenishing groundwater and soil water in riparian areas [*Workman and Serrano*, 1999; *Girard et al.*, 2003]. The area inundated by the 2003 peak flow when beaver dams were absent was limited to a narrow zone immediately adjacent to the river channel. Flooding was confined mainly to the 0.9 ha floodplain, inundating gravel bars and low-lying oxbows that were partially buried. The pattern of floodplain hydrologic connectivity we observed was consistent with the conceptual model of *Tockner and Stanford* [2002], which predicts that floods with a frequency of 10 years, such as the 2003 peak flow, should connect oxbows to rivers. Thus streamflows with recurrence intervals >10 years are necessary to flood the riparian area, which has a higher elevation than the oxbows.

[29] Beaver create ponds that not only impound water but raise water tables adjacent to ponds via increased hydraulic head, area of soil-water interface, and duration of soil-water contact [*Gurnell*, 1998; *Naiman et al.*, 1988; *Hammerson*, 1994]. These processes can be spatially limited in headwater valleys that are steep and narrow. In our study of an unconfined reach of the Colorado River, we found the main hydrologic effects of beaver were downstream of the dam rather than the upstream pond. The area affected by beaver extended hundreds of meters laterally and downstream of two in-channel dams that created the hydraulic head necessary to raise river water above the river banks, which substantially increased the probability of overbank flooding at a given stream discharge. Such extensive beaver effects are possible where rivers are small enough to be dammed and valleys are broad and flat enough to allow river water to spread across large areas. The flooded conditions in riparian areas affected by dams support the assumption that func-

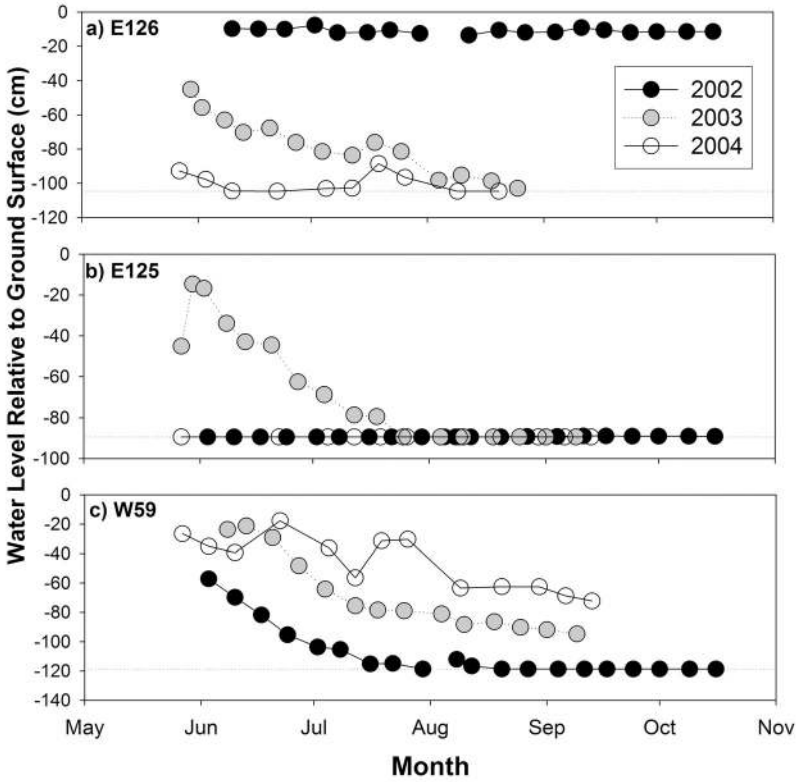


Figure 7. Hydrographs of wells (a) E126, (b) E125, and (c) W59 showing how either beaver dams (2002 and 2004) or overbank flow (2003) influenced water levels. The solid circles in Figure 7a are associated with the influence of the lower beaver dam, the shaded circles in Figure 7b are associated with overbank flood that occurred in 2003, and the open circles in Figure 7c are associated with the influence of the upper beaver dam. The dotted line in each plot indicates the bottom of the well, so data points on this line may be at or below these values.

tional beaver dams can create and maintain extensive riparian wetlands.

[30] The areal extent of flooding by the lower and upper dams was controlled by a combination of height of the water ponded behind in-channel dams relative to height of river banks and a valley topographic relief that allowed beaver to create a network of off-channel dams, ponds, and canals on the surrounding terrace. These off-channel features allowed beaver to access new foraging areas and expand territories [*Hodgdon and Lancia*, 1983; *Gurnell*, 1998; *Baker and Hill*, 2003]. This network resulted in the creation of multiple surface flow paths [*Woo and Waddington*, 1990] that functioned like a braided river system to spread water across the valley. This new water source can alter plant composition and increase productivity in a fashion analogous to flood irrigation for hay production in the western United States [*Peck et al.*, 2005]. We found the dynamic flow of water and associated nutrient-rich sediment from the river channel to the terrace can form off-channel beaver meadows that greatly expanded the riparian zone [*Westbrook*, 2005].

[31] Beaver flooded the valley throughout the streamflow recession and low-flow periods, although the spatial extent of flooding produced by the lower beaver dam decreased over the summer. Lowering of the pond water level below the top of the western portion of the dam allowed water to mainly flow through the dam instead of overtop of it [cf. *Woo and Waddington*, 1990]. The area flooded by the upper beaver dam was relatively constant throughout 2004 because the pond level was maintained at the top of the dam and water flowed around the dam onto the valley floor. Flooding could have been more extensive in wetter years such as 2003 than 2002 and 2004, if higher flows did not breach the dams.

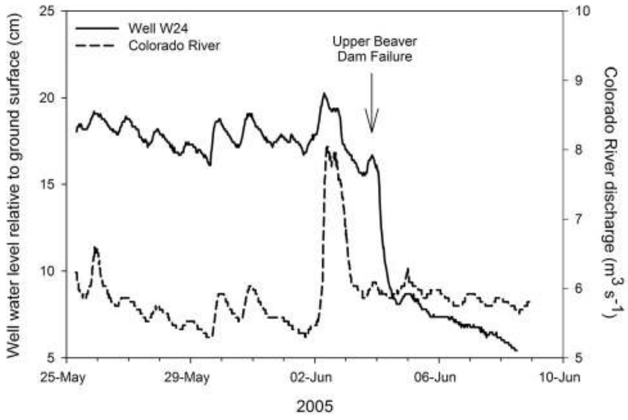


Figure 8. Groundwater levels in well W24 (located 670 m downstream of the upper beaver dam) and Colorado River discharge before and after failure of the dam show the water table dropped about 8 cm during 14 hours after of the dam failed.

[32] It is unlikely that all water spilled from the beaver ponds returned to the river. Evapotranspiration rates were likely higher because beaver detained water by spreading it across the valley surface and ponding it behind numerous small dams on the terrace [*Woo and Waddington*, 1990; *Burns and McDonnell*, 1998]. In addition, some beaver-distributed water likely recharged underlying alluvial aquifers in the valley, as the coarse-textured mineral soils had relatively high hydraulic conductivities (1×10^{-6} m s^{-1}) and the river water had a longer residence time in the riparian area because it was ponded behind off-channel dams.

4.2. Groundwater Flow Patterns and Water Table Fluctuations

[33] Higher groundwater levels and increased rates of groundwater recharge were observed upstream of the lower beaver dam in 2002 but not during the 2003 flood for the same area. Highly permeable channel sediments in association with relatively low hydraulic permeability of silt-loam riparian soils kept the hydraulic gradient oriented in the down-valley direction during the 2003 flood; a pattern that differs from the classic bank storage model, which predicts river water will be driven into the floodplain during bankfull events [*Pinder and Sauer*, 1971]. Strong aquifer anisotropy has been shown to reduce infiltration and maintain flow gradients parallel with the stream, thereby limiting water exchange between the river and riparian area [*Chen and Chen*, 2003]. In contrast, the hydraulic gradient on the floodplain east and west of the lower Beaver pond changed from a down-valley direction toward the valley center because of the increased elevation of stream stage behind the dam during the summer of 2002. Increased river-riparian soil interaction time due to the beaver dam appeared to compensate for the strong anisotropy of the system, permitting increased bank infiltration. Others have also found increased aquifer recharge upstream of a beaver dam [*Lowry and Beschta*, 1994; *Triska et al.*, 2000] and a debris dam [*Hill and Lymburner*, 1998].

[34] Groundwater levels indicated that water moved from the lower beaver pond west (perpendicular to the river) into floodplain soils, then flowed south down valley, and back east toward the river 300–600 m downstream of the dam. This pattern of groundwater flow was similar to the ‘‘looping’’ of groundwater flow around a beaver dam observed by *Lowry and Beschta* [1994] in central Oregon, but on a much larger scale. However, some researchers have found no influence of beaver activities on groundwater flow patterns. For example, *Woo and Waddington* [1990] found that beaver dams and ponds did not affect groundwater flow patterns in the subarctic wetlands surrounding James Bay, Canada because of the extremely low topographic relief. This suggests the groundwater flow effects of beaver activity may vary due to topographic relief or dam height, which can control the hydraulic gradient between the river and riparian area. The location of a beaver dam in relation to a valley’s hydraulic gradient and confinement may also affect groundwater flow patterns. The upper dam in our study site had no effect on the direction of groundwater flow, as the dam was located parallel to the direction of groundwater flow and was situated in a relatively confined portion of the valley. Thus efflux of river water was in the same direction as the valley groundwater flow gradient, which obscured the effects of the upper dam on flow direction. However, the presence of the upper dam steepened the down-valley hydraulic gradient for ~350 m south of the dam.

[35] The recharge of underlying alluvium and evapotranspiration can deplete groundwater stored in the soil during the summer, as suggested by the valley-wide decline in groundwater levels we observed, that were frequently to the base of the soil column or into the underlying gravel alluvium. The short duration of the natural flood was unable to maintain water tables near the soil surface in the riparian areas throughout the summer, a time when riparian plant water demand and infiltration into the aquifer are high and streamflow is low. Beaver dams can attenuate the rate of water table drawdown during the summer by providing a constant supply of water to the riparian area via surface and subsurface flow paths. Elevation maps of minimum water table levels showed the upper and lower beaver dams sustained groundwater levels equivalent to or higher in 2002 and 2004 than in 2003, which had 30% more snow water equivalent and a peak flow four times greater.

[36] Soil cores removed during the installation of our groundwater monitoring wells showed soil mottles above the elevation of the 2003 water table throughout the valley, which suggests soils had formed under conditions of long-duration soil saturation and anoxia. The mottles indicate that the water table was previously closer to the ground surface than during the flood conditions of 2003 when beaver dams were absent. The long-term river stage record shows natural overbank floods are too infrequent and too short in duration to explain the presence of mottled soils near the ground surface. The mottling is unlikely to be related to climate changes and its effects on streamflow during the post-Pleistocene deglaciation. This is supported by the analysis of *Woods* [2001], who showed that relatively large increases in river stage only have minor effects on riparian groundwater levels. The most likely explanation for soil mottle development is that beaver dams historically redirected water across the valley floor and maintained waterlogged soil conditions for extended periods.

4.3. Implications of Study Results

[37] This study analyzed the effects of only two beaver dams (2002 and 2004) on hydrological processes in the study area. The beaver population in recent years [*Mitchell et al.*, 1999], including during our study period, was only 5% of the 600 that were estimated to have been present in 1940 [*Packard*, 1947]. Operation of the Grand Ditch has reduced summer flows in the Colorado River by ~50% since ~1890, which likely altered how beaver dams affected the hydrologic processes in the valley. Beaver were likely more abundant in the valley and elsewhere before they were trapped during the period of European settlement in the early to mid 1800s [*Seton*, 1929].

[38] If the results of our intensive study were extrapolated to a time of more abundant beaver then the magnitude of their hydrologic effects may have encompassed nearly the entire study area. It is easy to visualize abundant beaver as key drivers of hydrologic processes in mountain valleys and other unconfined stream valleys throughout North America. Their role as a hydrologic engineer likely applies to similar Eurasian ecosystems as well; although the dam-building behavior of Eurasian beaver (*Castor fiber* Linnaeus) is

slightly less well developed than for North American beaver (*Castor canadensis*) [*Gurnell*, 1998].

[39] Beaver influence the hydrological processes that allow the development of floodplain soils and riparian vegetation. Therefore they also influence floodplain structure and function. Willows are the primary food and dam building material for beavers in our study area and in many other Rocky Mountain regions. However, willows are declining sharply in RMNP due to excessive herbivory by elk (*Cervus elaphus*) and moose (*Alces alces*) [*Peinetti et al.*, 2002; *Baker et al.*, 2005; *Gage and Cooper*, 2005] and in other regions due to herbivory by these species and livestock [*Baker and Hill*, 2003]. Without management to reduce competition for willows beaver could disappear and a critical driver of riparian area hydrologic regimes could be lost in RMNP and elsewhere.

5. Conclusions

[40] This study provides several new insights about the hydrologic role of beaver dams and floods in mountain valleys. A beaver dam present on the Colorado River in 2002 along with its associated terrace dams increased the extent, duration, and depth of surface inundation associated with floods. Further, the dam altered groundwater flow patterns over a large portion of the valley. In 2004, a second beaver dam built parallel with the down-valley groundwater flow steepened the groundwater flow gradient and created new surface water flow paths that inundated one quarter of the study area. In both cases, water left the Colorado River, flowed across the floodplain and terrace, and then back to the river far downstream of the dams. Most importantly, we found that the main effects of beaver on hydrologic processes occurred downstream of the dams rather than being confined to the near-pond area. The presence of mottled soils near the ground surface throughout the study area suggests that hydrologic processes driven by beaver dams played a key role in the soil development by maintaining waterlogged soil conditions for extended periods. The effects of beaver on hydrologic processes support the paradigm that they can create and maintain the structure and function of riparian wetlands along medium-gradient stream systems.

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B. W. Baker, U.S. Geological Survey, Fort Collins Science Center, 2150 Centre Avenue, Building C, Fort Collins, CO 80526-8118, USA.

D. J. Cooper, Department of Forest, Rangeland, and Watershed Stewardship, Colorado State University, Fort Collins, CO 80523-1472, USA.

C. J. Westbrook, Department of Geography, University of Saskatchewan, 9 Campus Drive, Saskatoon, SK, Canada S7N 5A5. (cherie.westbrook@usask.ca)