HYDROLOGICAL PROCESSES
Hydrol. Process. **15**, 609–620 (2001)
DOI: 10.1002/hyp.173

Analysis of groundwater exchange for a large plains river in Colorado (USA)

Arne Sjodin, William M. Lewis Jr.* and James F. Saunders III
Center for Limnology, Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO 80309-0216, USA

Abstract:

Complete daily water budget information was assembled for a 105 km segment of the South Platte River in the plains region below Denver, CO, for the period 1983–1993. The data were used in testing the possibility that dependence of alluvial exchange mechanisms on stage height, as shown by models of alluvial exchange, allows alluvial exchange to be predicted continuously over a given reach through use of statistical information on river discharge. The study segment was divided into an upper and a lower reach; daily alluvial exchanges for each reach were estimated by the method of residuals. The two reaches show small (15%) but statistically significant annual differences in rates of exchange. For each reach, there is a seasonal pattern (2·5-fold oscillation) in alluvial discharge to the channel, reflecting seasonality in recharge of the alluvium by irrigation. At discharges up to 40 m^3/s (82nd percentile), alluvial discharge to the channel occurs at a rate independent of river discharge. Above 40 m^3/s, net alluvial discharge into the channel is progressively reduced; at 60 m^3/s (92nd percentile) there is no net alluvial exchange. At still higher river discharges, water is lost to the alluvium through bank storage at a rate that is linearly related to the logarithm of discharge. Annually, alluvial discharge accounts for 15–18% of water entering the study segment, and alluvial recharge through bank storage accounts for 2–4% of water leaving the segment. Alluvial recharge through bank storage at the highest discharges can, however, exceed low-flow alluvial discharge rates by five-fold over short intervals. Even though daily alluvial exchanges vary widely, they can be estimated at r^2 values above 80% on the basis of reach, season, and river discharge. Copyright © 2001 John Wiley & Sons, Ltd.

KEY WORDS alluvial groundwater; river discharge; seepage; recharge; water balance

INTRODUCTION

Rivers with permeable or semi-permeable channels that are flanked by alluvial deposits of high hydraulic conductivity are likely to show significant losses to bank storage at high flow and subsequent discharge of bank storage with declining flow (Moench *et al.*, 1974; Jordan, 1977; Kondolf *et al.*, 1987). Analysis of these exchanges can be complicated by heterogeneity in alluvial deposits (Sharp, 1977), asymmetry of channel morphology (Whiting and Pomeranets, 1997), and stream bank phenomena that are difficult to quantify (Barlow *et al.*, 2000). Modelling of exchange between channel and aquifer has become increasingly sophisticated, however, and presently can incorporate factors such as hydraulic heterogeneity and recharge to the aquifer independent of bank storage (Squillace, 1996; Barlow *et al.*, 2000; Moench and Barlow, 2000).

Modelling of alluvial exchange has dealt mainly with individual episodes of high discharge. The results of modelling suggest, however, that an extended period of record with numerous changes in flow might show a high degree of regularity in the relationship between alluvial exchange and channel discharge (e.g. Squillace, 1996; Barlow *et al.*, 2000). Such regularity would be explained by loss of flow to bank storage at high flow in amounts closely related to discharge (or stage height) in the main channel, return of bank storage to the channel at rates dependent on elapsed time and hydraulic conductivity of the alluvium, and transmission

---

* Correspondence to: Professor W. M. Lewis Jr., Center for Limnology, University of Colorado at Boulder, Cooperative Institute for Research in Environmental Sciences, Campus Box 216, Boulder, Colorado 80309-0216, USA. E-mail: lewis@spot.colorado.edu

Received 17 September 1998
Accepted 8 August 2000

of watershed-based alluvial recharge to the channel at low flow. If these mechanisms could be described statistically, they would provide a basis for predicting the direction and amount of alluvial exchange over extended intervals involving complex changes in discharge. The possibility of close statistical relationships between channel discharge and alluvial exchange, as expected from mechanisms that are known to govern alluvial exchange, is tested here over two plains reaches of the South Platte River, Colorado, that are subject to aquifer recharge through irrigation.

STUDY SITE

The South Platte River drains an area of 62 900 km^2, most of which lies in northeastern Colorado (Figure 1). Its headwaters, which are fed primarily by snowmelt, are located near the Continental Divide southwest of Denver. There is a physiographic transition zone from mountains to plains near Denver, below which the South Platte becomes a plains river with a meandering course and low gradient. The study site is located in the plains region.

Annual precipitation in the montane portion of the South Platte watershed is generally more than 75 cm/year, but the plains portion of the drainage is generally semi-arid (below 38 cm/year; Dennehy *et al.*, 1995). Flow is highly regulated throughout the drainage for municipal and agricultural water supply; the South Platte River has been subject to diversions since 1868 (Eschner *et al.*, 1983). Present water management involves storage

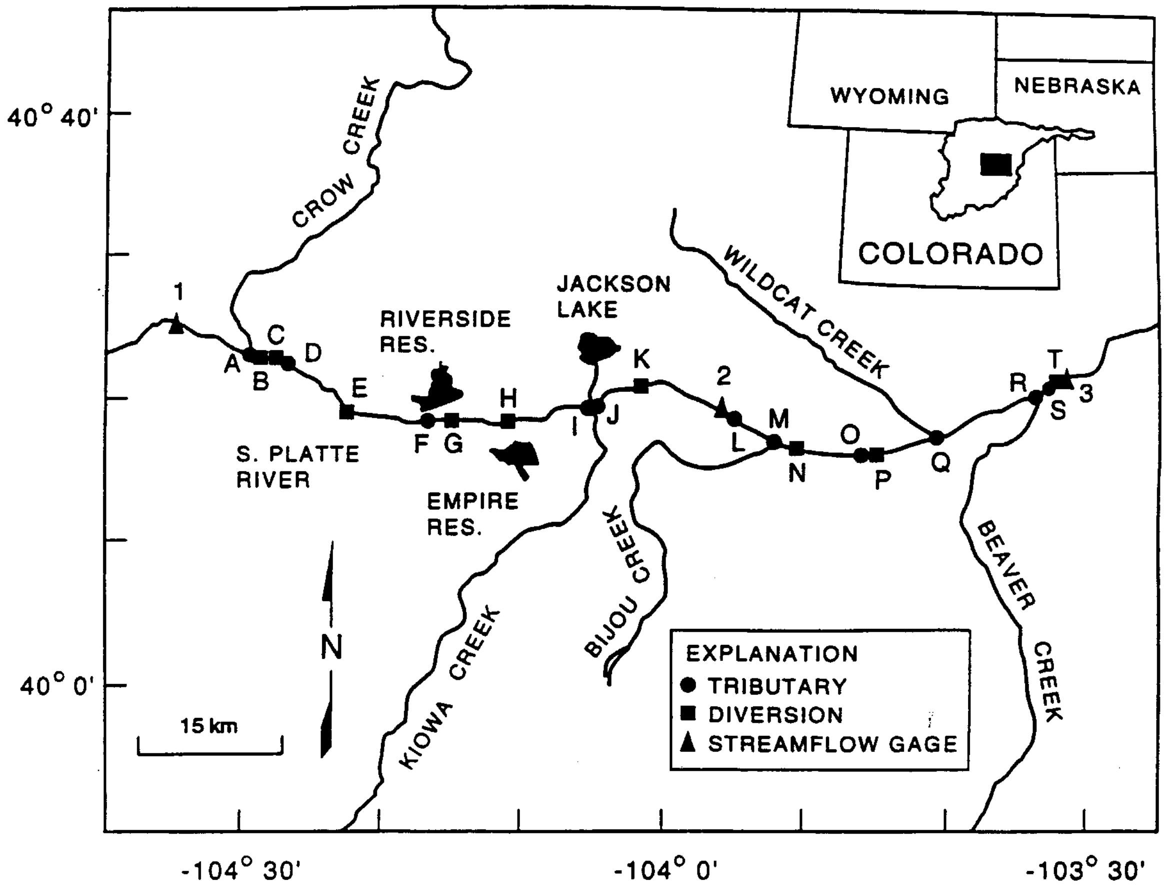

Figure 1. Map of the study area showing the location of gages, tributaries, and diversions (see Table I for codes)

of seasonal runoff, diversions and pumping for agricultural and municipal supply, and addition of wastewater discharges to the river.

Even though flow on the South Platte is extensively regulated, seasonal patterns are evident (Hurr *et al.*, 1975; Knopf and Scott, 1990). Peak discharges occur typically in May and June and can reach or exceed 10 times the historical mean discharge (34 m^3/s for the period 1976–1994 at the Kersey gage). In spite of an increase in consumptive use of water, the mean discharges in the South Platte River have not exhibited a downward trend, probably because of interbasin transfer of water (Eschner *et al.*, 1983; Knopf and Scott, 1990).

The study area lies between Kersey and Cooper Bridge on the South Platte main stem (Figure 1). This segment, which is 105 km long, is gaged at three points. The upper gage is at Kersey (USGS 06754000), the middle gage is 67 km downstream near Weldona (USGS 06758500), and the lower gage is at Cooper Bridge (USGS 06759910), 38 km from the Weldona gage. These three gages divide the study segment into two reaches for the purposes of hydrologic analysis.

In the upper reach, between the Kersey and Weldona gages, there are four tributaries (Figure 1), as listed in Table I. Of these, only Crow Creek is important to the water budget of the South Platte main stem; the

Table I. Location and names of tributaries, diversions, and sampling points for the study site on the South Platte River. Map references correspond to Figure 1

Tributary or diversion name	River (km)	Map reference
South Platte near Kersey	0·0	1
Crow Creek	7·2	A
Empire Canal	8·4	B
Riverside Canal	9·8	C
Illinois Ditch	9·8	C
Box Elder Creek	10·3	D
Bijou Canal	21·1	E
Putnam Ditch	21·1	E
Corona Ranch Ditch	21·1	E
Lost Creek	30·6	F
Jackson Lake Inlet	32·3	G
Weldon Valley Ditch	41·4	H
Kiowa Creek	49·7	I
Jackson Lake Outlet	51·3	J
Fort Morgan Canal	60·0	K
South Platte near Weldona	66·6	2
Weldon Valley Ditch Return	66·8	L
Bijou Creek	72·9	M
Bijou #2 Release	72·9	M
San Arroyo Creek	72·9	M
Upper Platte & Beaver Canal	75·8	N
Deuel & Snyder Ditch	75·8	N
Badger Creek	86·3	O
Lower Platte & Beaver Canal	87·4	P
Tremont Ditch	87·4	P
Snyder–Smith Ditch	87·4	P
Wildcat Creek	90·6	Q
Beaver Creek	102·8	R
Antelope Creek	103·6	S
North Sterling Canal	104·1	T
Union Ditch	104·1	T
South Platte at Cooper Bridge	105·1	3

other three tributaries were dry more than 99% of the time between 1983 and 1993. Releases from Jackson Lake, an off-channel storage reservoir, add flow to the upper reach from October to April. Nine diversions draw water from the upper reach (Figure 1, Table I).

In the lower reach, there are six tributaries (Figure 1, Table I), of which four (San Arroyo, Badger, Antelope, and Beaver) had no flow between 1983 and 1993. Bijou Creek and Wildcat Creek had flow for most days in the same period, and the discharge of Bijou Creek was augmented by return flows from Bijou #2 Reservoir. Weldon Valley ditch also returns flow to the South Platte. Seven diversions withdraw water from the lower reach (Table I). Of these seven, two (Snyder–Smith and Union) operated infrequently (less than 3% of the time between 1983 and 1993).

All of the tributaries to the study segment have small, semi-arid watersheds. Most of these tributaries carry diversion water for municipal or agricultural use (e.g. Crow Creek and Bijou Creek; USGS, 1964). Some tributaries have been dammed by the Natural Resources Conservation Service (e.g. Kiowa Creek; USGS, 1964).

The valley fill alluvium in the study area is made up of Holocene sands and gravels that rest on shale of Cretaceous origin (Dennehy *et al.*, 1993). The alluvium is 3·2 to 12·9 km wide and 6·1 to 36·6 m deep (Hurr *et al.*, 1972a–c). The alluvial material is relatively coarse; its hydraulic transmissivity ranges from 58 to 462 m^3/day/m (Hurr *et al.*, 1972a–c). Head drop between alluvial groundwater and the channel is typically low ($<$30 cm at low flow; Morel-Seytoux *et al.*, 1979). The South Platte River has a braided or anastomosing channel (Ward *et al.*, 1989; Knopf and Scott, 1990) with an average slope close to 0·13%. The channel substrate in the study area of the river is shifting sand and gravel and has an organic content of less than 1% (Ward *et al.*, 1989). The mean width of the upper reach varies seasonally between 110 and 220 m (lower reach, 120 to 310 m). The depth at median discharge is 0·40 m at the top of the two reaches (24 m^3/s), 0·46 m at the junction of the two reaches (18 m^3/s), and 0·40 m at the bottom of the lower reach (13 m^3/s).

METHODS

Hydrologic data for this study consist of daily mean gage values from calibrated water-stage recorders (precision ±15%) for the main stem and the prominent tributaries and diversions, and instantaneous diversion flows (usually taken from calibrated staff gages, precision ±15%) for the smaller ditches, canals, and tributaries in the study segment. Tributary flows were obtained from the daily water information log maintained by the state government (Water Commissioner for Colorado Water District 1, personal communication). Daily average flows for diversions were also obtained from state sources (Water Resources Division of the Office of the Colorado State Engineer, personal communication). The three gages on the main stem are operated by the United States Geological Survey, which is the source of data on discharge at these locations (http://waterdata.usgs.gov/nwis-w/co/). The period of record for the study is 1 October 1983 to 30 September 1993.

Net alluvial exchange was estimated for each day as the residual of discharge between gages after correction of the upstream discharge for measured input (tributaries, releases from storage reservoirs) and measured output (diversions). The residuals were estimated separately for each of the two study reaches (Kersey to Weldona, Weldona to Cooper Bridge). Estimation of alluvial exchange in this manner causes the final estimate to include not only alluvial exchange, but also any systematic or random errors associated with the empirical measurements from which the residuals were obtained. Alluvial exchanges in this segment of the South Platte are, however, sufficiently large that the presence of estimation error does not preclude quantitative estimation of alluvial exchange by the method of residuals. As shown below in the results section, a basis for quantitative estimates can be demonstrated through standard deviations for water-budget components and by concordance of seasonal patterns and discharge–exchange relationships across the two reaches.

Both positive and negative exchanges occur between the South Platte and its adjacent alluvium. Movement of water from the alluvium to the main channel will be designated here as ‘alluvial discharge’. Movement of water into the alluvium will be designated as 'alluvial recharge', which can occur from the channel (through bank storage) or from the watershed (through irrigation). Only the daily net flux is estimated here; surface waters constantly move between the channel and the hyporheic zone, whether the overall net flux is positive or negative with respect to the channel (Gordon *et al.*, 1992).

Unrecorded direct runoff could inflate estimates of alluvial discharge. For this reason, field inspection of the study segment was conducted on seven dates (1994: 5 January, 15 February, 7 June, 21 June; 1995: 3 August, 2 November). The inspection showed that unrecorded surface runoff is negligible by comparison with alluvial exchange.

Evapotranspiration losses from the water surfaces are part of the residual from which alluvial exchange is estimated. Estimates show, however, that evapotranspiration would fall below 5% of alluvial exchange, and would for this reason not be quantitatively significant.

Net movement of water between the channel and the alluvium is expressed here as flux per unit distance (m^3/km/s; positive for alluvial discharge, negative for alluvial recharge).

RESULTS

Water budget

Figure 2 provides an overview of the discharge of the South Platte River at the upper end of the study reach (Kersey gage) over the interval of study (1983–1993). Hydrographs for other points along the study segment show similar patterns.

As shown by Figure 2, the discharge of the South Platte has an annual peak during May, June, or July, reflecting seasonal runoff. In addition, brief peaks may occur at other times in connection with individual storms. For 1983–1993, median discharge of the South Platte at Kersey is 24 m^3/s; the 10th

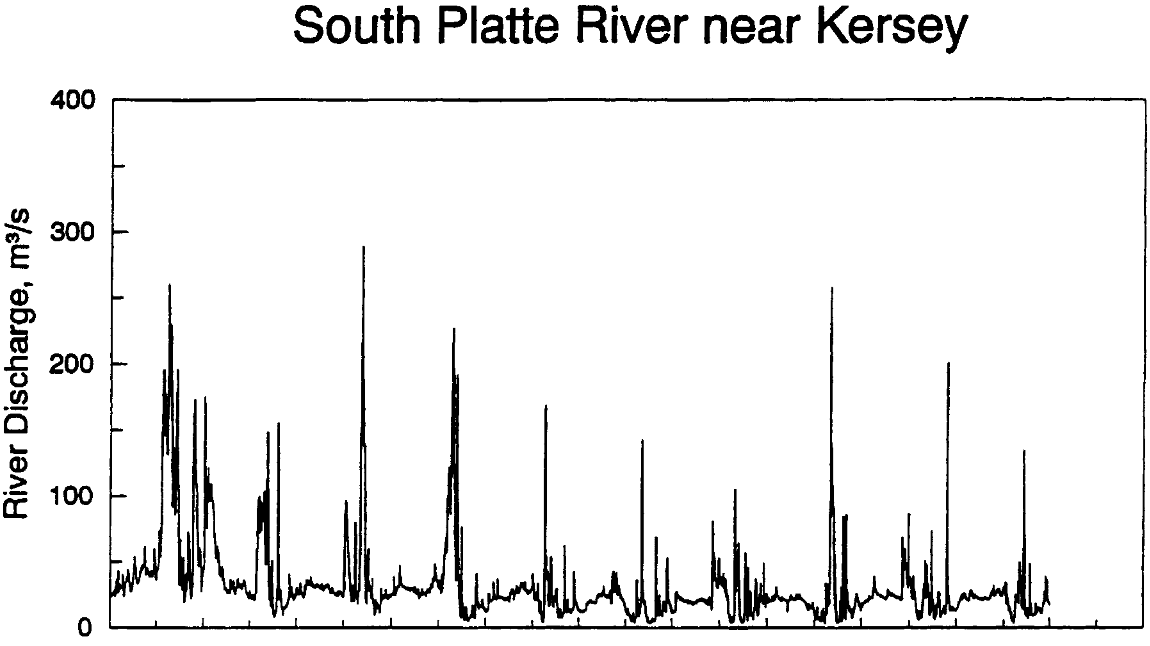

Figure 2. Hydrograph of the South Platte River near Kersey, at the upper end of the study segment, over the interval between October 1983 and September 1993

percentile is 11 m^3/s and the 90th percentile is 56 m^3/s (Figure 3). Low discharges can occur in any month. There is considerable interannual variation caused by differences in the amount of snowpack in the headwaters.

Table II gives the volumes and percentages for each water budget component as a daily mean for each month, as well as the annual mean volume across the 10-year study interval for the upper reach (Kersey to Weldona) and the lower reach (Weldona to Cooper Bridge). The means for input and output in specific months reflect the seasonality of snowmelt at high elevation (May and June) and of irrigation withdrawals, which in July and August can even exceed main stem output for the upper reach.

The seasonal pattern for tributary flow is different from that of the main stem. High tributary flows begin as early as April and extend through September or October. Although tributaries are an essential component of the water budget, they in no case make up more than 9% of the budget, and in most months they comprise less than 2% for the upper reach and less than 4% for the lower reach.

Alluvial exchange is much larger than tributary flow. In the upper reach, alluvial discharge adds an average of 17% annually to the source side of the water budget for the channel (15% for the lower reach), and accounts for as much as 30% during July. Alluvial discharge occurs in all months, and ranges about two- to three-fold around a peak coinciding with the highest diversions for irrigation. Alluvial recharge through bank storage is temporally erratic and ranges much more widely in magnitude than alluvial discharge; it is seldom large in winter months, and shows a peak coinciding with the months of highest stream discharge. On an annual basis, alluvial recharge through bank storage is about one-fifth the size of alluvial discharge for the upper reach (one-sixth for the lower reach).

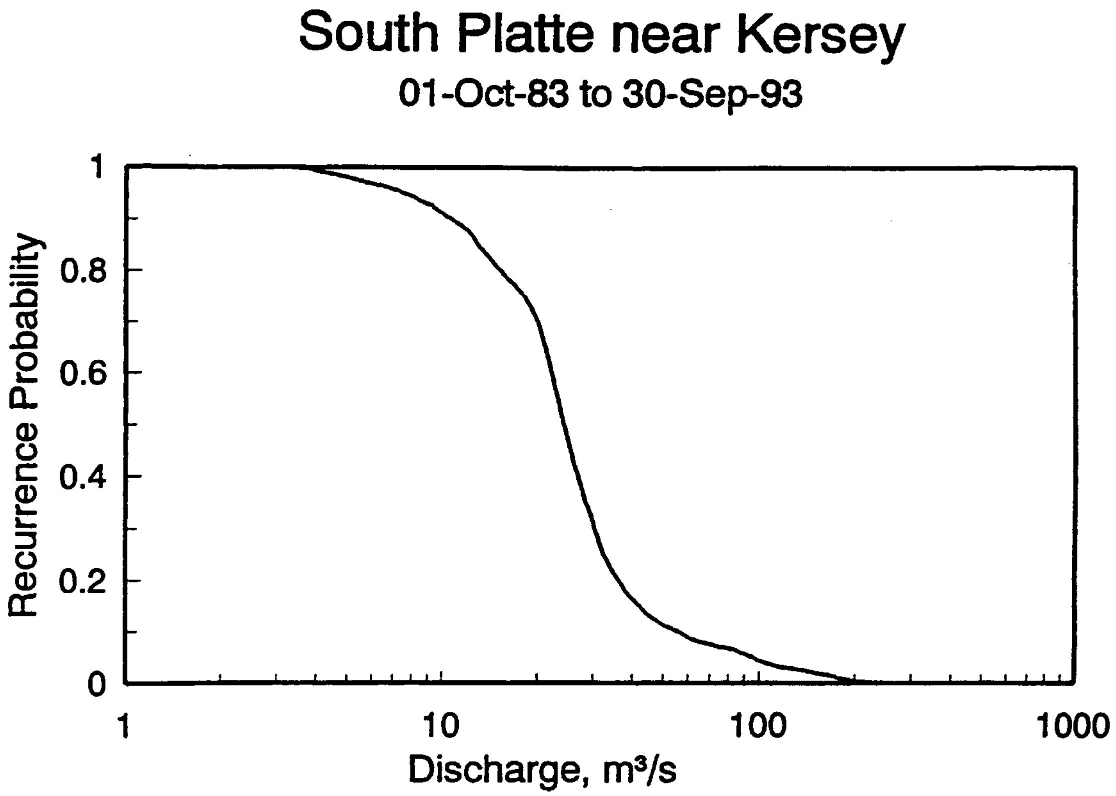

Figure 3. Recurrence probability plot for discharge of the South Platte River near Kersey, at the upper end of the study segment, over the interval between October 1983 and September 1993

Table II. Water budgets of the upper reach (Kersey to Weldona) and lower reach (Weldona to Cooper Bridge) as monthly and annual daily means across the 10 years of the study (1983–1993). Volumes are in thousands of cubic meters per day

	Sources								Losses							
	Platte input		Tributaries		Reservoir releases		Alluvial discharge		Platte output		Irrigation		Reservoir storage		Alluvial recharge[a]	
Month	Volume	Percent	Volume	Percent	Volume	Percent	Volume	Percent	Volume	Percent	Volume	Percent	Volume	Percent	Volume	Percent
Upper Reach																
Jan	2324	83·7	12	0·4	0	0·0	442	15·9	2110	76·0	112	4·0	545	19·6	11	0·4
Feb	2444	81·8	13	0·4	0	0·0	530	17·7	2072	69·4	133	4·5	757	25·4	25	0·8
Mar	2701	85·1	16	0·5	0	0·0	457	14·4	1532	48·3	326	10·3	1273	40·1	44	1·4
Apr	3036	82·1	34	0·9	49	1·3	579	15·7	2223	60·1	488	13·2	811	21·9	177	4·8
May	4534	87·4	90	1·7	12	0·2	553	10·7	3483	67·1	757	14·6	508	9·8	441	8·5
Jun	4986	87·0	79	1·4	38	0·7	629	11·0	3152	55·0	944	16·5	964	16·8	672	11·7
Jul	1730	61·3	51	1·8	190	6·7	851	30·1	1148	40·7	1341	47·5	240	8·5	93	3·3
Aug	2029	64·7	50	1·6	276	8·8	782	24·9	1531	48·8	1330	42·4	116	3·7	160	5·1
Sep	2115	67·1	75	2·4	156	4·9	806	25·6	1796	57·0	1037	32·9	294	9·3	26	0·8
Oct	2482	79·8	24	0·8	3	0·1	600	19·3	1772	57·0	554	17·8	738	23·7	46	1·5
Nov	2681	84·6	15	0·5	0	0·0	474	14·9	1603	50·6	221	7·0	1336	42·2	9	0·3
Dec	2294	82·4	12	0·4	0	0·0	479	17·2	1805	64·8	148	5·3	826	29·6	7	0·2
Annual	2778	79·9	39	1·1	61	1·8	599	17·2	2017	58·0	619	17·8	699	20·1	143	4·1
Lower Reach																
Jan	2110	80·9	44	1·7	0	0·0	454	17·4	2188	83·9	4	0·2	412	15·8	4	0·2
Feb	2072	82·8	47	1·9	0	0·0	384	15·3	2098	83·8	22	0·9	274	11·0	110	4·4
Mar	1532	81·4	55	2·9	0	0·0	294	15·6	1568	83·3	51	2·7	185	9·8	78	4·2
Apr	2223	85·9	139	5·4	0	0·0	226	8·7	1880	72·7	239	9·3	367	14·2	100	3·9
May	3483	86·2	159	3·9	0	0·0	398	9·9	3185	78·8	415	10·3	300	7·4	140	3·5
Jun	3152	77·4	164	4·0	0	0·0	756	18·6	3161	77·6	477	11·7	361	8·9	73	1·8
Jul	1148	74·4	130	8·4	0	0·0	265	17·2	872	56·5	591	38·3	13	0·8	67	4·4
Aug	1531	78·6	149	7·7	0	0·0	267	13·7	1282	65·8	592	30·4	0	0·0	73	3·7
Sep	1796	77·5	185	8·0	0	0·0	336	14·5	1661	71·7	474	20·4	153	6·6	29	1·2
Oct	1772	74·5	133	5·6	0	0·0	473	19·9	1180	49·6	316	13·3	868	36·5	15	0·7
Nov	1603	77·4	68	3·3	0	0·0	400	19·3	1012	48·9	98	4·7	929	44·9	30	1·5
Dec	1805	82·4	44	2·0	0	0·0	342	15·6	1548	70·7	15	0·7	590	26·9	37	1·7
Annual	2017	80·4	110	4·4	0	0·0	382	15·2	1799	71·7	276	11·0	371	14·8	63	2·5

[a] Recharge from channel to alluvium, i.e. bank storage.

Annual diversions to irrigation and storage are very large (39% of the water budget for the upper reach and 26% for the lower reach), and occur throughout the year.

Analysis of alluvial exchange

Daily alluvial exchanges were clustered by month across the 10-year interval and plotted as a function of channel flow. The plots show two features: (1) alluvial discharge is constant for a given month when the channel flow is below about 40 m^3/s; and (2) there is a progressive decline in alluvial discharge beginning at about 40 m^3/s and leading to reversal of alluvial exchange (recharge through bank storage) at channel flows greater than approximately 60 m^3/s. The increase in alluvial recharge with increasing channel flow is approximately linear on a logarithmic scale. These patterns are evident for both reaches and in all months, but are clearest for months showing the broadest range of flow across the 10-year period of study (e.g. April: Figure 4). Figure 5 summarizes the relationship of alluvial exchange to channel flow.

Table III shows the alluvial discharge under low to moderate flows for each month. Although alluvial discharge shows no trend below channel flows of about 40 m^3/s, channel flows below 28 m^3/s were used in constructing Table III so that results would not be influenced by higher variance in alluvial discharge that develops in some months between 30 and 40 m^3/s. The standard deviation is considerably smaller than the mean for any given month, indicating that the means can be used in making quantitative estimates of alluvial discharge for the two reaches. As shown by the table, alluvial discharge at low to moderate flows varies

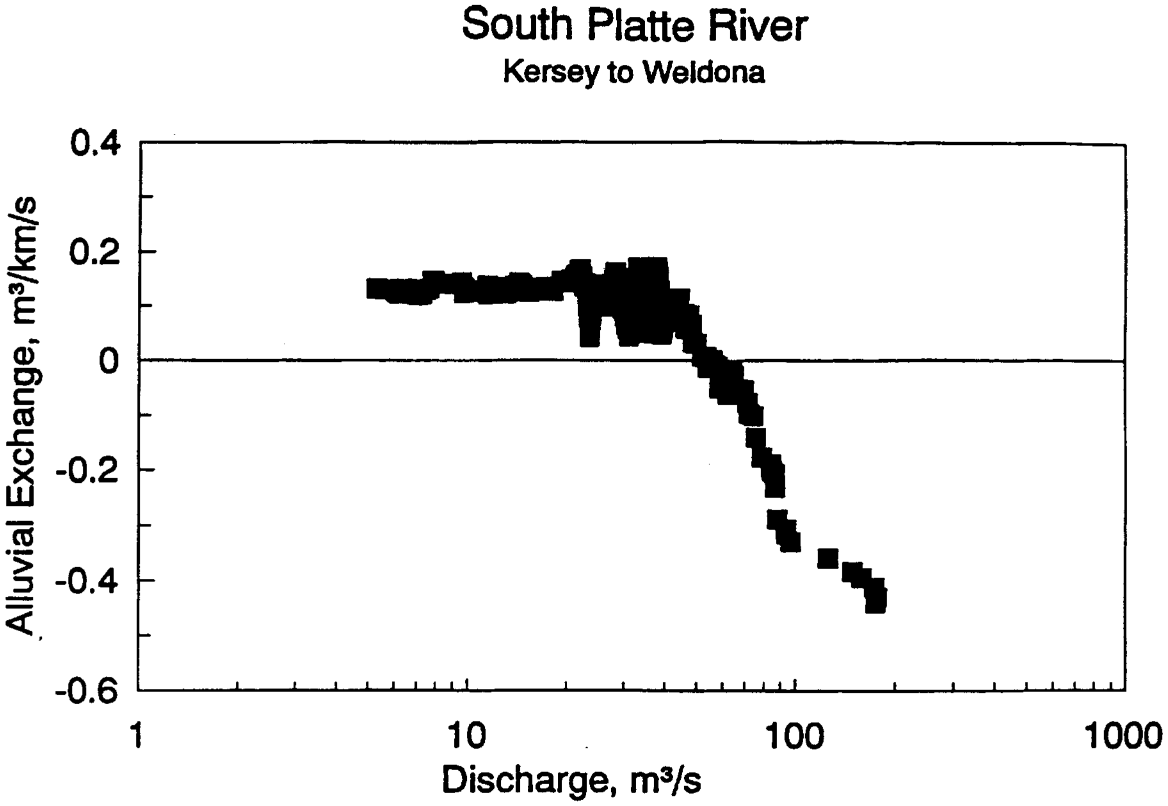

Figure 4. Relationship between discharge and alluvial exchange for the study reach between Kersey and Weldona, for all days in the month of April, 1984–1993 (points are 9-day moving averages)

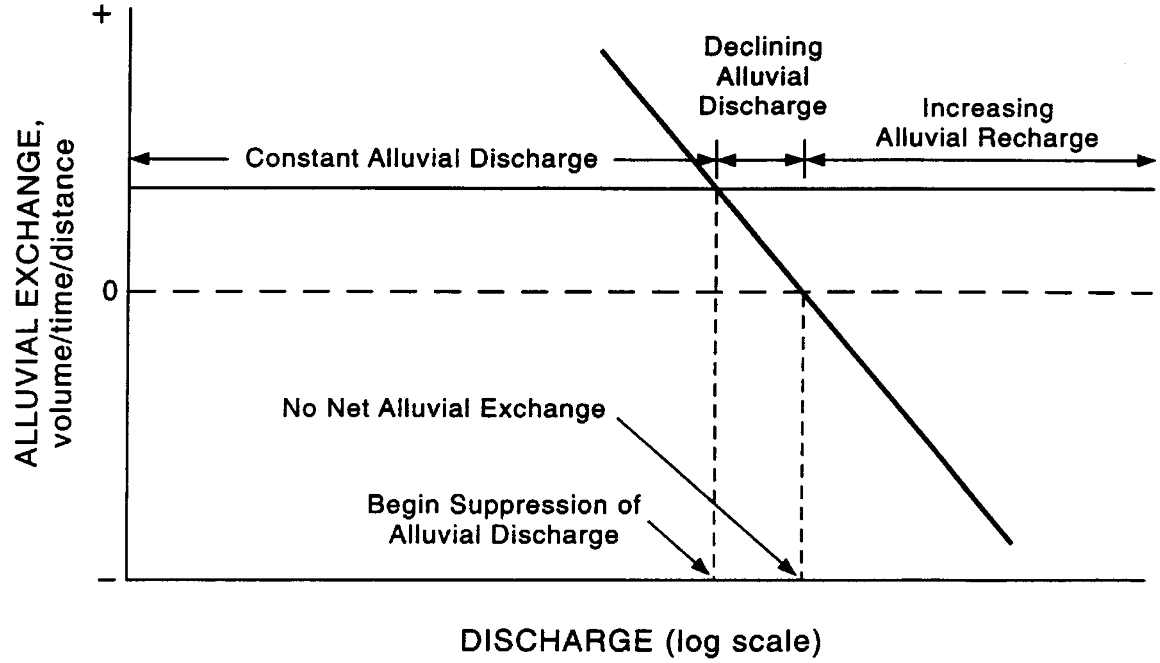

Figure 5. Illustration of the components for statistical analysis of alluvial exchange

approximately two-fold across months and is highest during the months of highest irrigation rates. Alluvial discharge is very substantial, however, even when irrigation is not occurring. The table also shows that alluvial discharge is higher in the upper reach of the study segment than in the lower reach. While the difference between reaches is statistically significant on an annual basis, it is relatively small (annual mean 0·12 $m^3/km/s$ for the upper reach vs. 0·10 $m^3/km/s$ for the lower reach). These rates are higher than ones that have been estimated for reaches nearer to Denver, where irrigation is less prevalent (0·05 to 0·09 $m^3/km/s$; Dennehy *et al.*, 1995).

Quantification of the relationship between discharge and alluvial flux at high channel flows involves estimation of the slope of a line relating alluvial exchange to channel flow above approximately 40 m^3/s, where alluvial exchange begins to show a response to increasing channel flow. The intersection of this line with a line of zero slope representing the alluvial discharge at low to moderate channel flow completes the statistically-based description of alluvial exchange in relation to channel flow (Figure 5). Quantification of the positions of both lines is possible only for months when substantial numbers of data points (daily flows) exceed 40 m^3/s. There are four such months (April, May, June, August), each of which was analyzed separately for the two reaches.

Relationships of channel flow to alluvial exchange above 40 m^3/s for the four months of the upper reach were very similar, as were those of the four months for the lower reach. Thus the data for the four months were pooled for each reach (Table IV). Further analysis showed only minor differences in relationships between reaches. Therefore, all of the data were pooled and the result is as shown in Table IV. The data in Table IV are based on flows above 42·5 m^3/s; repetition of the analysis with various other discharge cutoff points above but close to 40 m^3/s showed little difference from results given in Table IV. As indicated by the table, alluvial discharge is constant up to about 40 m^3/s (82nd percentile), declines to zero at about 60 m^3/s (92nd percentile), and then gives way to progressively greater alluvial recharge through bank storage above 60 m^3/s.

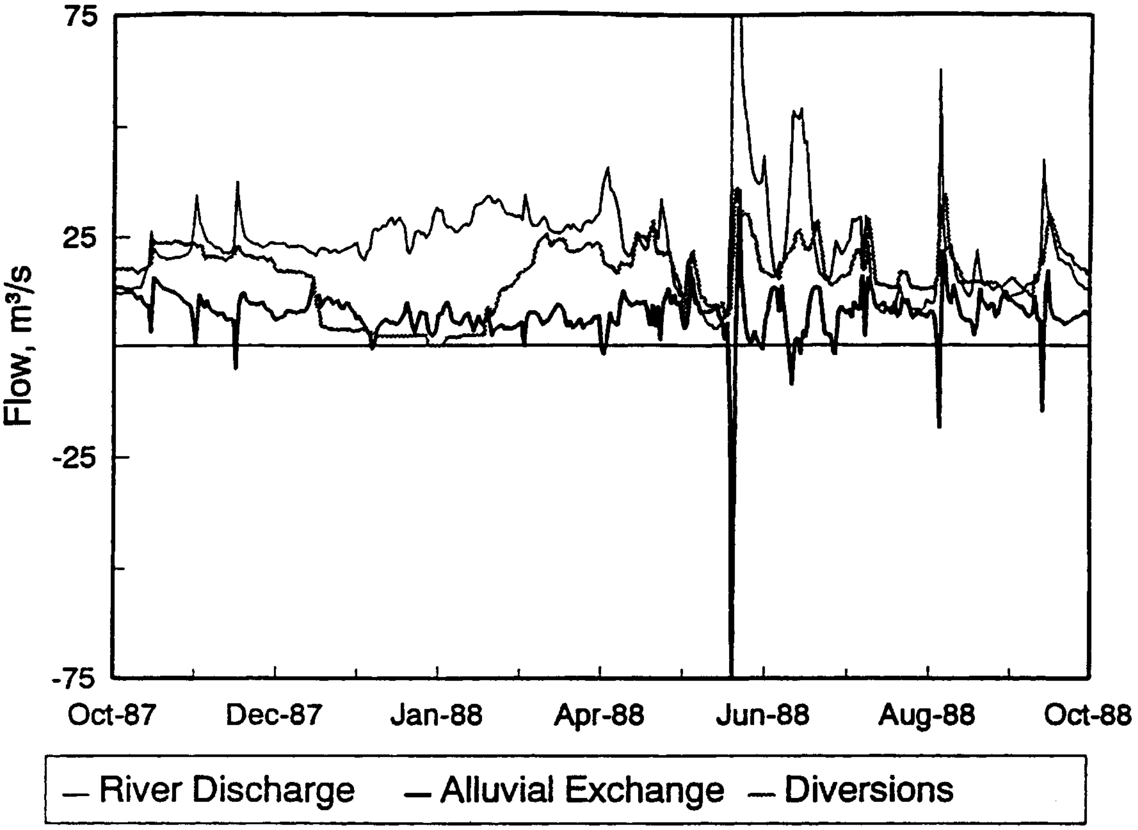

Figure 6. Alluvial exchange, channel discharge, and diversions (water year 1988) for the South Platte between Kersey and Weldona as calculated from equations developed in the study (see text)

Table III. Estimates of alluvial discharge at river discharges ≤ 28 m^3/s over a 10-year period of record (1983–1993)

	Upper reach (Kersey to Weldona)			Lower reach (Weldona to Cooper Bridge)		
Month	Mean discharge (m^3/km/s)	Standard deviation	*n*	Mean discharge (m^3/km/s)	Standard deviation	*n*
Jan	0·073	0·019	212	0·070	0·021	212
Feb	0·089	0·023	176	0·082	0·022	202
Mar	0·081	0·012	154	0·073	0·024	255
Apr	0·129	0·020	149	0·111	0·023	196
May	0·129	0·019	181	0·109	0·036	203
Jun	0·152	0·025	125	0·110	0·051	184
Jul	0·150	0·026	236	0·132	0·034	284
Aug	0·141	0·015	258	0·132	0·033	268
Sep	0·150	0·015	240	0·143	0·022	243
Oct	0·107	0·027	246	0·104	0·026	275
Nov	0·088	0·012	170	0·083	0·021	248
Dec	0·085	0·021	193	0·081	0·017	232
Annual	0·116[a]	0·018	2339	0·103	0·008	2801

[a] Significantly higher than for lower reach ($p < 0.05$).

Table IV. Results of the regression of alluvial exchange (m^3/km/s) vs. log of river flow for flows above 42·5 m^3/s (all relationships are significant at $p < 0{\cdot}001$)

Statistic	Upper reach	Lower reach	Combined reaches
N	486	344	830
Slope[a]	0·779	0·722	0·750
Standard error, slope	0·014	0·015	0·011
Constant	1·39	1·25	1·32
Standard error, constant	0·056	0·038	0·053
r^2	0·857	0·872	0·840
Suppression flow[b]	43·17	38·67	41·05
Equilibrium Flow[b]	60·86	53·86	57·54

[a] Δy = exchange as m(^{3}/km/s), Δx = logarithm of discharge (m^3/s).

[b] Suppression flow is that at which alluvial discharge first begins to decline in response to increasing flow; equilibrium flow is that at which alluvial exchange = 0.

DISCUSSION

Temporal variation in the rate of alluvial exchange for the South Platte study region is related to river reach, time of year, and discharge. River reach, which accounts for variation of about 10% in annual exchange, is the smallest of these three sources of variation. Season, which accounts for a two- to three-fold variation among months, is the second largest source of variation. River discharge is the largest cause of variation; the rate of exchange at the highest flows is of opposite sign to exchange at low flows, and is five times as high.

Some variation between adjoining river reaches is expected because of differences in the amount of irrigation recharge per unit area of land, as well as other factors involving characteristics of the alluvium or channel morphology. Also, for a given reach, seasonal variation is expected because of the linkage between discharge from the alluvium and recharge of the alluvium by irrigation, which is extensive, seasonal, and includes lands very near the channel.

The relationship between channel flow and alluvial exchange is the most important and most complex of the three sources of variation. At the highest flows, there are large losses to bank storage. As expected, there is a direct relationship between the amount of channel flow and the rate of loss to bank storage (e.g. Barlow *et al.*, 2000). At flows below 40 m^3/s, alluvial discharge is steady because it is explained primarily by movement of irrigation recharge through the alluvium to the channel. In the South Platte, alluvial discharge by this mechanism at low to moderate flows is substantial, in contrast to ephemeral streams or streams lacking alluvial recharge in the watershed (e.g. Lane *et al.*, 1971). In fact there is considerable alluvial discharge to the channel even up to relatively high flows (*c.* 80th percentile).

Multiple processes characterize the transition (40–60 m^3/s) between high and low to moderate channel flow. A rise in channel flow within this range appears to change the hydraulic gradient for alluvial water, thus suppressing alluvial discharge. Separately, and probably concurrently, a rise in channel flow may induce bank storage in the unsaturated portion of the alluvium. In addition, channel flows between 40 and 60 m^3/s at times of receding flow may lead to a return of water from bank storage over intervals as long as several weeks (Whiting and Pomeranets, 1997). The data show, however, that return of bank storage is small (*c.* 20%) relative to total alluvial discharge.

The results of the South Platte study indicate that basic mechanisms of alluvial exchange, as described analytically and numerically in previous detailed studies of specific high discharge events, indicate feasibility for statistical description of exchange over a long record of flows in at least some rivers where alluvial exchange is important. For the South Platte, the statistical approach shows a high degree of predictability for alluvial exchange through its quantification of the relationship between river discharge and losses to bank storage at high flow, steady discharge from the alluvium in any given month at low to moderate flow, and a transition between these states as the hydraulic gradient for alluvial discharge changes under the influence of change in river discharge. Information of this type can be applied directly to geochemical and biogeochemical studies that require estimates of exchange continuously over long periods of time, rather than on an event basis, and for which the calibration of numerical models is impractical.

ACKNOWLEDGEMENTS

We thank Kevin Dennehy and other staff scientists of the US Geological Survey Water Resources Division in Denver, CO, for financial support and access to information in the completion of this project, and Brad Wind of the Northern Colorado Water Conservancy District for assembling hydrologic records for us. We thank George Hornberger for helping us find relevant literature and for suggesting fruitful ways to interpret the mechanisms that might apply to our study site.

REFERENCES

Barlow PM, DeSimone LA, Moench AF. 2000. Aquifer response to stream-stage and recharge variations. II. Convolution method and applications. *Journal of Hydrology* **230**: 211–229.

Dennehy KF, Litke DW, Tate CM, Heiny JS. 1993. South Platte River Basin—Colorado, Nebraska, and Wyoming. *Water Resources Bulletin* **29**: 647–683.

Dennehy KF, Litke DW, McMahon PB, Heiny JS, Tate CM. 1995. Water-quality assessment of the South Platte River Basin, Colorado, Nebraska, and Wyoming—analysis of available nutrient, suspended-sediment, and pesticide data, water years 1980–92 *Water-Resources Investigations Report No. 94-4095*. US Geological Survey.

Eschner TR, Hadley RF, Crowley KD. 1983. Hydrologic and morphologic changes in channels of the Platte River Basin in Colorado, Wyoming, and Nebraska: a historical perspective Geological Survey Professional Paper 1277: *Hydrologic and Geomorphic Studies of the Platte River Basin*. US Geological Survey; A1-A39.

Gordon ND, McMahon TA, Finlayson BA. 1992. *Stream Hydrology: An Introduction for Ecologists*, Wiley: Chichester, UK.

Hurr RT, Schneider Jr. PA, *et al.* 1972a. *Hydrogeologic characteristics of the valley-fill aquifer in the Greeley reach of the South Platte River Valley, Colorado* (Open-File Report) US Geological Survey.

Hurr RT, Schneider Jr. PA, *et al.* 1972b. *Hydrogeologic characteristics of the valley-fill aquifer in the Weldona reach of the South Platte River Valley, Colorado* (Open-File Report) US Geological Survey.

Hurr RT, Schneider Jr. PA, *et al.* 1972c. *Hydrogeologic characteristics of the valley-fill aquifer in the Brush reach of the South Platte River Valley, Colorado* (Open-File Report) US Geological Survey.

Hurr RT, Schneider Jr. PA, Minges DR. 1975. *Hydrology of the South Platte River Valley, Northeastern Colorado Colorado Water Resources Circular 28*. Colorado Water Conservation Board, Denver, CO.

Jordan PR. 1977. Stream flow transmission losses in western Kansas. *Journal of the Hydraulics Division, American Society of Civil Engineers* **103**: 905–918.

Knopf FL, Scott ML. 1990. Altered flows and created landscapes in the Platte River Headwaters, 1849–1990. Sweeney JM (ed.). *Management of Dynamic Ecosystems*, The Wildlife Society, West Lafayette, IN; 47–70.

Kondolf GM, Maloney LM, Williams JG. 1987. The effects of bank storage and well pumping on base flow, Carmel River, Monterey County, CA. *Journal of Hydrology* **91**: 351–369.

Lane LJ, Diskin MH, Renard KG. 1971. Input–output relationships for an ephemeral stream channel system. *Journal of Hydrology* **13**: 22–40.

Moench AF, Barlow PM. 2000. Aquifer response to stream-stage and recharge variations. I. Analytical step-response functions. *Journal of Hydrology* **230**: 192–210.

Moench AF, Sauer VB, Jennings ME. 1974. Modification of routed stream-flow by channel loss and base flow. *Water Resources Research* **10**: 963–968.

Morel-Seytoux HJ, Illangasekare T, Peters G. 1979. Field verification of the concept of reach transmissivity. *The Hydrology of Areas of Low Precipitation, Proceedings of the Canberra Symposium, December 1979 IASH–AISH Publication No. 128*; 355–359.

Sharp J. 1977. Limitations of bank-storage model assumptions. *Journal of Hydrology* **35**: 31–47.

Squillace PJ. 1996. Observed and simulated movement of bank-storage water. *Groundwater* **10**: 121–134.

USGS (1964). Compilation of surface water records of the United States, October 1950 to September 1960. Part 6-B. Missouri River Basin below Sioux City. *Water-Supply Paper No. 1730.* US Geological Survey.

Ward JV, Voelz NJ, Harvey JH. 1989. Groundwater faunas as indicators of groundwater quality: the South Platte River system. *Completion Report No. 150.* Colorado Water Resources Research Institute, Colorado State University, Fort Collins, CO.

Whiting PJ, Pomeranets M. 1997. A numerical study of bank flow and its contribution to stream flow. *Journal of Hydrology* **202**: 121–136.