METAMORPHOSIS OF SOUTH PLATTE AND ARKANSAS RIVERS, EASTERN COLORADO

C. T. Nadler
Mobil Oil Company, Denver

S. A. Schumm
Colorado State University, Fort Collins

Abstract: The Arkansas and South Platte Rivers in eastern Colorado have changed dramatically during the past 150 years. Earlier, they were relatively straight, wide, braided, intermittent streams. However, percolation of irrigation water into and through valley alluvium has raised water tables, and flow regulation has produced more uniform flow into the rivers. As a result new floodplains formed, and bank and floodplain vegetation became denser, as if a climatic change to more humid conditions had occurred. The rivers became narrower and more sinuous due to perennial stream flow, abstraction of sediment with irrigation water, and a decrease in discharge during drought. Three reaches of these rivers responded differently to the changes. The South Platte River and a reach of the Arkansas River narrowed and developed a single thalweg. In contrast, a reach of the Arkansas River at Bent's Old Fort began to meander as a result of an increase of suspended sediment load. All of the reaches are near a pattern threshold.

INTRODUCTION

The South Platte and Arkansas Rivers in eastern Colorado are excellent examples of rivers that have undergone dramatic historic changes that are so extensive that they can be termed a metamorphosis. River metamorphosis has been defined as the complete change of river morphology; for example, from meandering to braided and vice versa (Schumm, 1969).

Measurements and reports by explorers in the early part of the 19th century show that both rivers were wide, shallow, braided streams. Agricultural development was much the same in both basins. However, the rivers today exhibit different channel characteristics (Figs. 1, 2, and 3). The purpose of this study is to document the changes in both rivers during the last 150 years; to develop geomorphic and sedimentologic models to correspond to the changes; and to explain why the rivers responded differently to similar external influences. It is hoped that river metamorphosis can be better understood and predicted in the future from studies of this sort.

The South Platte and Arkansas River originate in the mountains of central Colorado and flow eastward on valley alluvium of Pleistocene and Holocene age. Both rivers experienced large seasonal fluctuations in discharge due to snow melt (Powell, 1889; Coues, 1895; Parkman, 1948), and they decreased in volume as they crossed the semiarid plain, owing to seepage and evaporation losses.

Agriculture began in both basins immediately following the first gold rush to Colorado in 1858. By 1895 there were 20 major irrigation diversions on the Arkansas River between Pueblo and Kansas (Fig. 4), and similar diversions were occurring on the South Platte River.

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Fig. 1. Aerial photograph of South Platte River near Greeley in July, 1977.

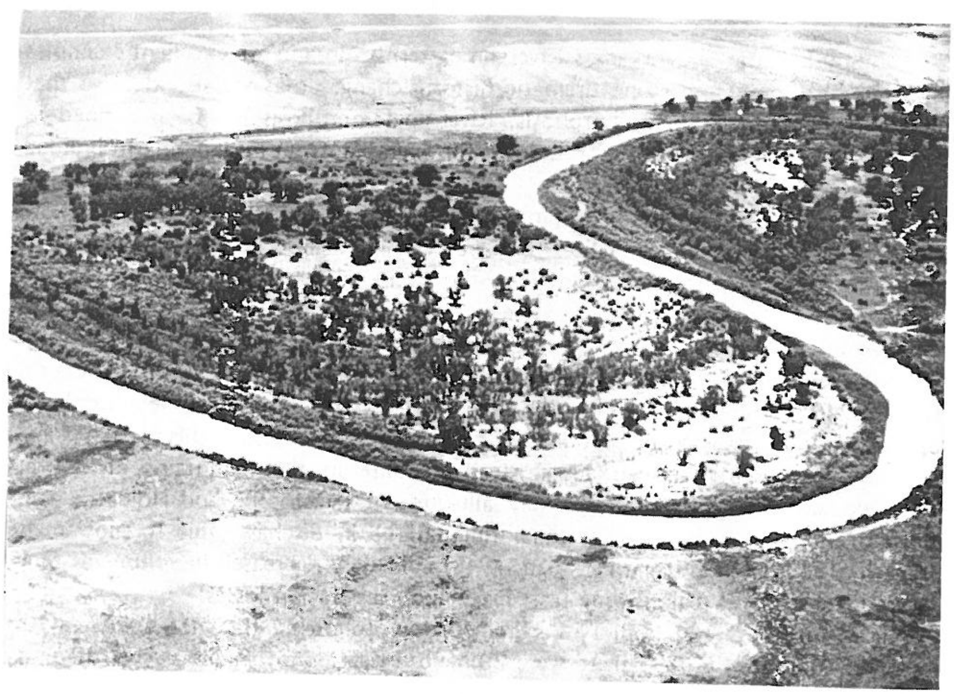

Fig. 2. Aerial photograph of Arkansas River near Bent's Old Fort in June, 1977.

Fig. 3. Aerial photograph of Arkansas River near Carlton in June, 1977.

Between 1885 and 1897, recharge to the rivers began because of crop irrigation practices, and the hydrologic character of the rivers started to change (Boyd, 1897; Parshall, 1922; Steinel and Working, 1926; Freeman and Bolster, 1909; Bittenger and Stringham, 1963). The effect of irrigation was to raise the water tables above the river beds in late summer and to change stream flow from intermittent to perennial.

Droughts between 1926 and 1940 and in the early- to mid-1950s temporarily reduced mean annual and peak discharges of the rivers (Nadler, 1978), but the only permanent change of mean annual or peak discharge has been below John Martin Dam. Therefore, the major hydrologic change was from intermittent to perennial stream flow.

As the hydrologic character of the rivers and their floodplains changed, there were changes in the types and amounts of floodplain vegetation. According to reports by James (1823), Fremont (1956), Emory (1848), Hale (1854), and Vestal (1939), it is apparent that woody vegetation was sparse along the rivers. There were fewer shrubs on the floodplains, and cottonwood groves alternated with prairie. It is apparent that there is more vegetation along the rivers today (Fig. 3). This increase in vegetation reflects an increase in soil moisture due to a higher water table, as a result of increased irrigation.

The Arkansas River has experienced the additional impact of the introduction of an exotic species. Salt cedar (*Tamarix ramosissima*), a phreatophyte native to

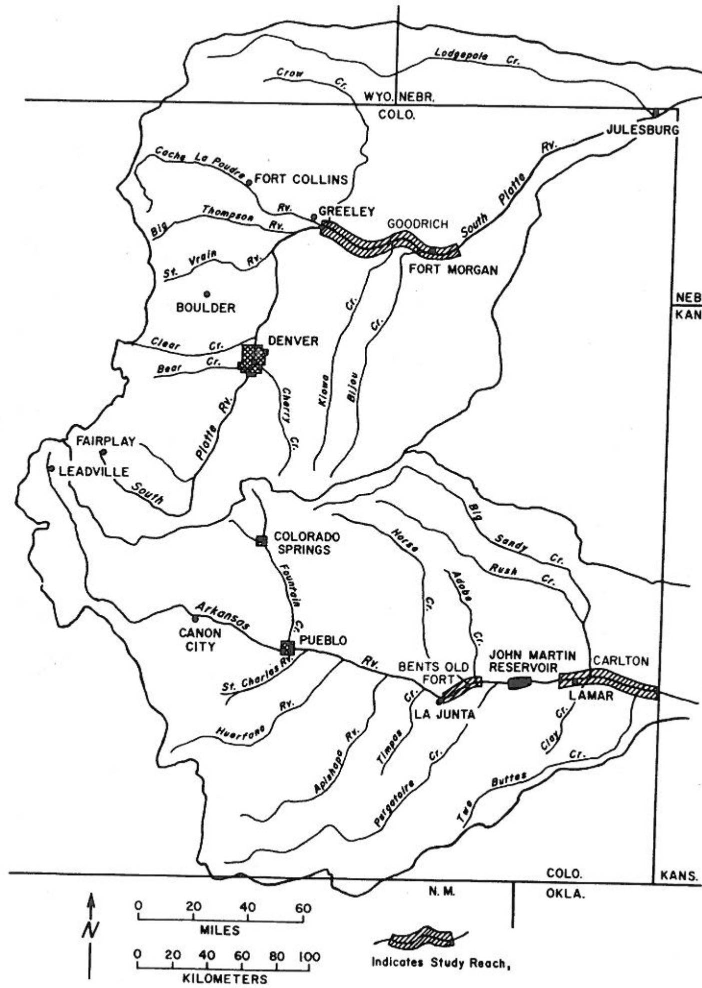

Fig. 4. Index map of South Platte and Arkansas Basins showing location of study reaches.

the Mediterranean, was first observed in the Arkansas Valley in 1913 near Lamar (Lindauer and Ward, 1968). Today, salt cedar thrives along many rivers in southwestern United States. Salt cedar reduces the efficiency of stream channels by increasing bank roughness and promoting deposition of sediment and channel construction (Robinson, 1958).

In summary, the hydrologic nature and type of floodplain vegetation of both rivers changed appreciably. As water tables rose and stream flows became perennial, floodplains were able to sustain denser vegetation. In addition, salt cedar invaded the Arkansas River Valley. These hydrologic and vegetative changes produced major morphologic changes along both rivers.

Methods

Based on map studies and aerial reconnaissance, it was determined that the South Platte River, unlike the Arkansas River, exhibits a uniform pattern throughout eastern Colorado. For this reason, one braided and one meandering segment of the Arkansas River were selected for study, as was one braided segment of the South Platte River (Fig. 4). These reaches were typical of those observed in Colorado.

Morphologic data were gathered from map and field measurements. Maps employed were U.S. Geological Survey 7.5′ series (ca. 1953, 1:24,000 and 30′ series (ca. 1890, 1:125,000), General Land Office maps (ca. 1860, 1:31,680), and U.S. Department of Agriculture map (Sweet and Inman, 1926, 1:63,360). Field measurement stations were selected within the study segments where the channels and floodplains were surveyed. One floodplain study site was selected within each of the study segments (e.g., Table 3).

Sediment was sampled from the channels at surveyed cross sections. Floodplain samples were taken from auger holes and pits. Sediment properties were calculated utilizing a computer program prepared by Werner (1970). Percentages of silt and clay in channel perimeters were calculated using the weighted mean method suggested by Schumm (1960).

Floodplain stratigraphy and cottonwood trees' (*Populus deltoides*) ages were useful in establishing the mode and rate of floodplain construction. The age of trees was determined by ring counts of selected trees. Local museums, newspapers, and government offices provided early photographs of the rivers. Written accounts of the rivers by early immigrants and basin development data were acquired from resources at the Colorado State University Library. Runoff and climatic data were taken from U.S. Geological Survey Water Supply Papers, and from U.S. Weather Bureau documents, respectively.

RIVER METAMORPHOSIS

South Platte River

Channel morphology: First descriptions of the South Platte River were made by James (1823) in 1819. He reported that the width of the river immediately above its confluence with North Platte River was about 823 m. Observation in the same general vicinity by Parkman (1948) in 1846, by Warren (1856) and Burton (1963) in 1863 were in general agreement with his estimate. In the study reach, 1967 maps indicate an average width of 445 m, with a range from 335 m to 610 m (Nadler, 1978). Slichter and Wolff (1906) claimed the width was between 457 m and 762 m throughout eastern Colorado in 1906. The 1952 maps show that the average width decreased to 61 m, with a range from 34 m to 101 m, which is only 14% of the 1867 width. Field surveys in 1977 indicate width had increased slightly to an average of 95 m, with a range of 61 m to 119 m, at nine stations.

Two estimates of bank heights were made in the 1860s. Sir Richard Burton (1963) estimated bank height at 1.5 m in 1863, and Ashley (1867) estimated bank height at 1.22 to 1.83 m near Fort Morgan. Mean bankfull depth was 1.5 m and mean width-depth ratio was 69 in 1977 for nine locations in the study reach (Nadler, 1978).

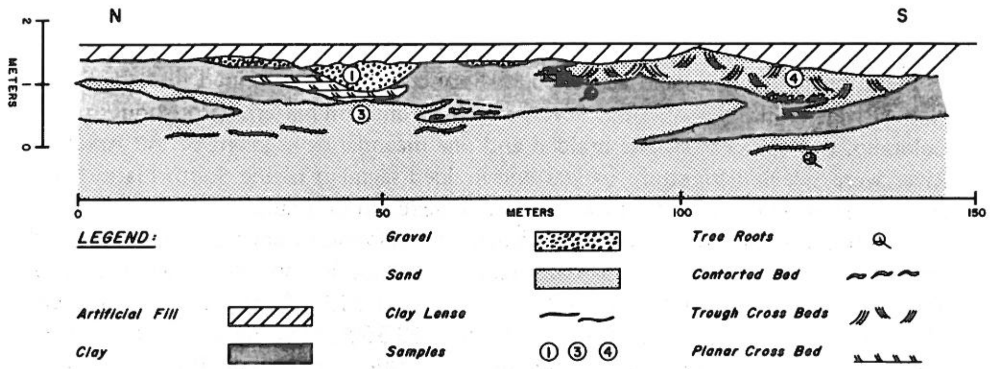

Fig. 5. Floodplain stratigraphy as exposed in pit near Goodrich.

Sinuosity has increased from 1.05 to 1.15 during the period 1867 to 1952. Although width has increased slightly since 1952, sinuosity today appears to be about the same as it was in 1952. Average gradient has remained at about 0.0013.

Between 1867 and 1952, there was an increase in the number of islands and degree of braiding, although this may be deceptive. The 1952 maps, made from aerial photographs, include all islands regardless of size. It is likely that the 1867 maps do not include all the smaller islands, but it is clear that South Platte River evolved from a classic braided river to a narrower river during the 20th century.

Sedimentology and stratigraphy: Sediment samples were taken from three stratigraphic units in a gravel pit at Goodrich (Fig. 4). Figure 5 shows the sample locations in the floodplain and Table 1 lists the results of the above sieve analysis. The unit

Table 1. Sediment Data, South Platte River

Sample	Median grain size (mm/ϕ)	Mean grain size (ϕ)	Standard deviation (ϕ)	Percent silt-clay in sample	Percent silt-clay in channel
#1, Goodrich[a]	2.42/-1.277	-1.045	1.516	0.17	
#3, Goodrich[a]	1.86/-0.895	-0.815	1.915	1.61	
#4, Goodrich[a]	1.69/-0.757	-0.984	1.700	0.05	
Kersey Bank[b]	0.061/4.041	3.578	0.821	59.60	2.91
Kersey Bed[b]	0.878/0.188	-0.029	1.836	1.72	
Masters Bank[b]	0.062/4.017	3.276	1.260	53.63	2.59
Masters Bed[b]	1.23/-0.297	-0.338	1.615	1.51	
Weldona Bank[b]	0.473/1.080	0.935	1.809	7.99	1.22
Weldona Bed[b]	0.992/0.012	-0.190	1.924	1.08	
Snyder Bank[b]	0.107/3.230	3.134	1.012	39.89	0.99
Snyder Bed[b]	1.39/-0.473	-0.546	1.636	0.08	

[a]Floodplain samples as shown on Figure 5 are single samples.
[b]Bed and bank samples are composite samples.

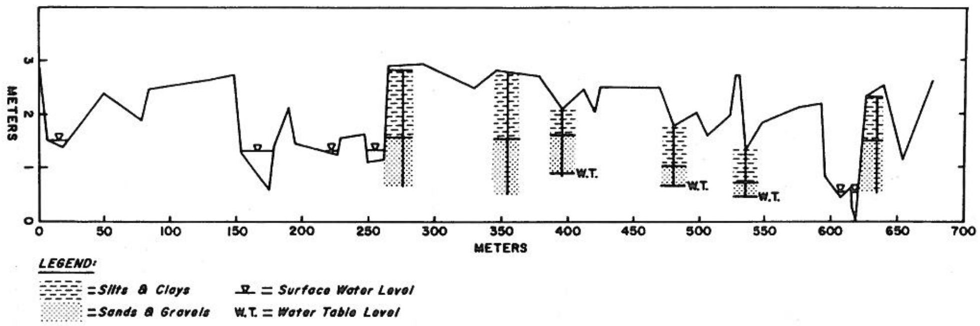

Fig. 6. Cross section of floodplain at Goodrich showing topography and stratigraphy.

from which Sample 3 was taken was of greater lateral extent than of the coarser-grained units overlying it. For this reason, it is assumed that this unit represents the channel deposits of the 19th century South Platte River. Modern channel sediment characteristics are presented for four other locations in Table 1 for comparison. The sediment properties do not appear to have changed significantly during the past 150 years.

The gravel pit at Goodrich provided an excellent opportunity for a study of floodplain construction in conjunction with channel changes (Fig. 5). The ground surface at the cross section was obscured by overburden from excavation of the pit. However, a cross section (Fig. 6) surveyed immediately downstream depicts the braided pattern on the floodplain, which can also be seen from the air (Fig. 1), and four pits and two river-cut banks revealed the relation between floodplain topography and stratigraphy. The topographic lows, which were channels, are underlain by thin layers of silts and clays which are, in turn, underlain by sands and gravels. The topographic highs, which appear as longitudinal bars in plan view, are underlain by thicker units of silts and clays.

The exposure in the gravel pit revealed a variety of deposits with little vertical or lateral extent, overlying an extensive basal study unit (Fig. 5). Based on their relation to adjacent units and their sedimentary structures, the discontinuous silt and clay units overlying the basal sand are interpreted as flood deposits on islands. Islands forming on emergent bars are generally underlain by sands and gravels (Reineck and Singh, 1975, p. 227). The silt and clay deposits, although similar to floodplain deposits, are separated from the floodplain by channel deposits (Fig. 5 at 50 and 125 meters) and were most likely deposited on islands. Tongues of sand extending laterally upward into the island deposits represent either the effects of wind or the last lateral shifts of the channel braids. The channel-shaped deposits at 50 and 125 meters (Fig. 5) were probably formed by reactivation of channel braids during floods.

Arkansas River

Channel morphology: Emory (1848) was first to record the width of the Arkansas River. He noted that between Pawnee River (central Kansas) and Bent's Old Fort, the

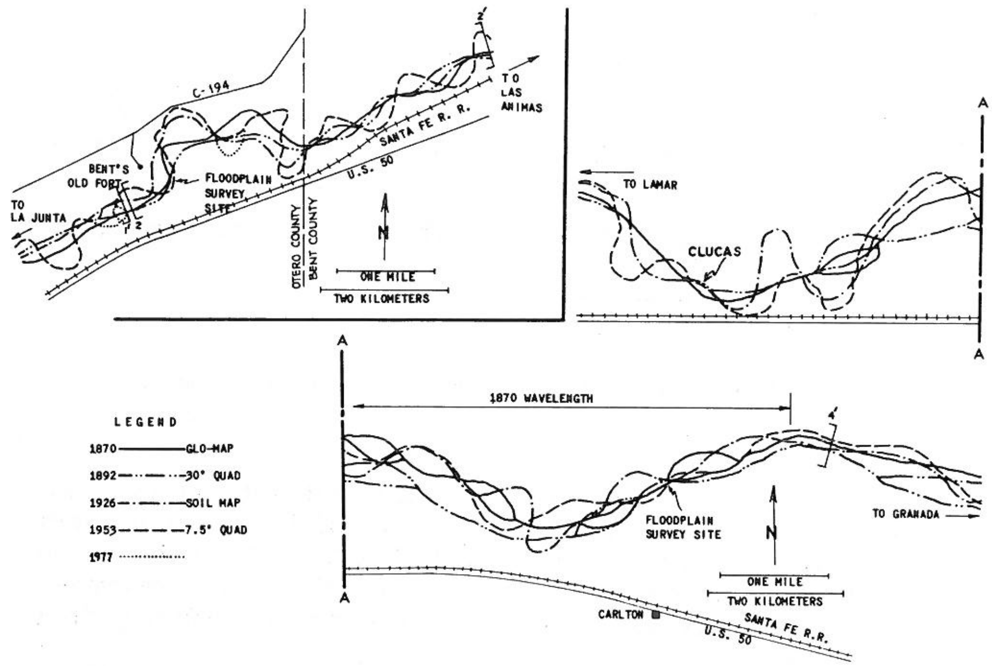

Fig. 7. Channel pattern changes of Arkansas River between 1870 and 1977.

river seldom exceeded 150 yards (137 m). Farnham (1906) and Parkman (1948) both stated that Arkansas River was, in places, a quarter of a mile (402 m) wide in the years 1839 to 1846. Perhaps wider reaches impressed these writers, whereas narrower ones went undocumented.

Emory (1848) commented on spatial changes. He noted that approximately 56 km downstream from Bent's Old Fort, at an area called "Big Timbers" (T22S, R48W), the river widened, and the banks on each side sloped gently towards the channel. Width data for 1879 confirm his observations.

Measurements in the Bent's Old Fort reach (Fig. 4) indicate that the river widened slightly between 1870 and 1892 (175 m to 215 m), and then it narrowed considerably between 1926 and 1952 (215 m to 46 m). The 1952 width was only 21% of the 1892 width. The upper half of the Carlton reach (Fig. 4) also widened between 1892 and 1952 (355 m to 145 m). The lower half of the Carlton reach has narrowed since 1870, mostly between 1926 and 1952 (375 m to 260 m to 38 m).

Bankfull depth of the Arkansas River prior to 1977 is difficult to ascertain. Emory (1848) noted that water depth at Bent's Old Fort was no more than knee-deep (approx. 0.46 m). Pike (Jackson, 1966) estimated bankfull depth at Great Bend, in central Kansas, at not more than 0.91 m. Vestal (1939) stated the banks of the river were between 0.91 to 1.22 m for most of its course. In 1977, the average bankfull depth was 1.14 m and width-depth ratio was 29.

The sinuosity of every reach of the river was greater in 1977 (1.43) than it was in 1870 (1.15) (Fig. 7). However, sinuosity has not changed significantly since 1952,

Table 2. Sediment Data, Arkansas River

Sample	Median grain size (mm/ϕ)	Mean grain size (ϕ)	Standard deviation (ϕ)	Percent silt-clay in sample	Percent silt-clay in channel
Casa Bridge Bank[a]	0.060/4.052	3.591	0.800	63.17	3.35
Casa Bridge Bed[a]	0.318/1.652	1.633	0.694	0.23	
Bent's Old Fort Bank[a]	0.061/4.027	3.620	0.702	55.98	5.01
Bent's Old Fort Bed[a]	0.248/2.010	1.917	0.618	0.81	
Countyline Bank[a]	0.060/4.060	3.775	0.530	65.90	3.78
Countyline Bed[a]	0.423/1.242	0.979	1.169	0.21	
Carlton Bank[a]	0.121/3.044	2.901	1.185	38.78	2.85
Carlton Bed[a]	0.928/0.108	-0.058	1.174	0.62	
Holly Bank[a]	0.175/2.511	2.724	1.195	34.78	1.98
Holly Bed[a]	0.697/0.521	0.286	0.951	0.00	
#2-H, Bent's Old Fort[b]	1.27/0.344	-0.409	2.301	1.97	
#0, Carton[b]	0.618/0.695	0.647	1.098	0.13	

[a]Bed and bank samples are single composite samples.
[b]Floodplain samples as shown in Figures 12 and 13 are single samples.

there have been minor changes in the river's course. The greatest increase in sinuosity occurred between 1926 and 1952 for every reach except Carlton (Fig. 7).

Sedimentology and stratigraphy: Analyses of modern and historic channel sediment are presented in Table 2. Sample 2-H is historic channel sediment at Bent's Old Fort (Fig. 8), and Sample O is historic channel sediment at Carlton (Fig. 9). Sample 2-H is located approximately in the 1926 channel and it is interpreted to be bed sediment of that time. It is the coarsest material found on the upper study segment. The river at Bent's Old Fort is presently composed of sand with a median

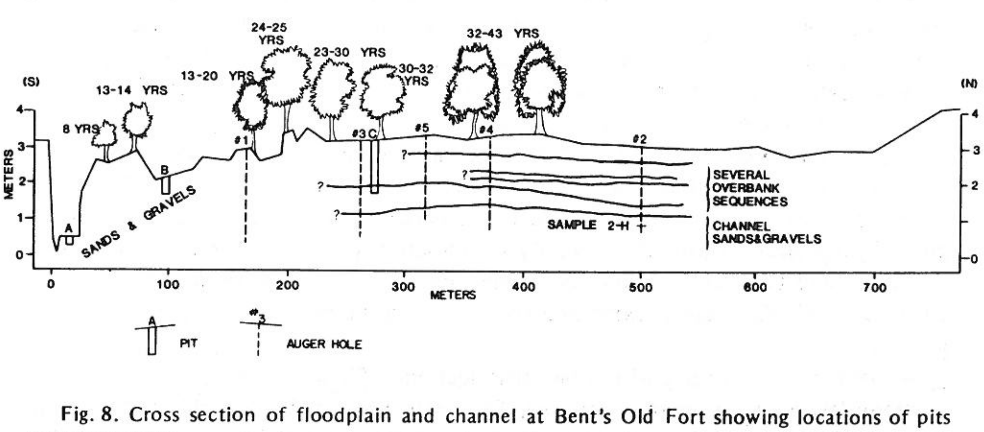

Fig. 8. Cross section of floodplain and channel at Bent's Old Fort showing locations of pits and auger holes.

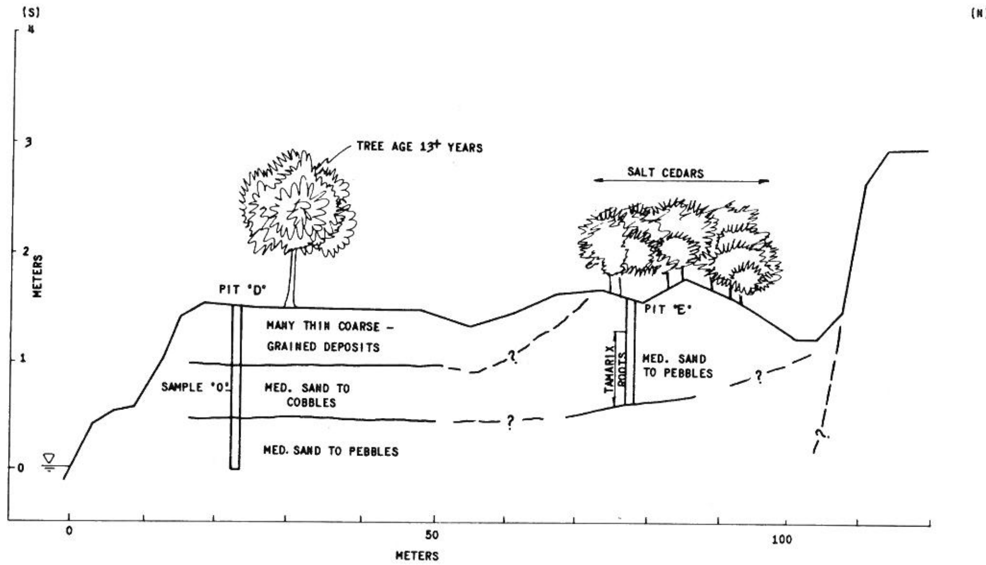

Fig. 9. Cross section of floodplain at Carlton showing locations of pits.

grain diameter considerably finer than the material in Sample 2-H. In addition, the channel perimeter at Bent's Old Fort contains more silt and clay than in the other study reaches (Table 2).

Channel sediment at Carlton is coarser than at Bent's Old Fort, and it contains less silt and clay. Although Carlton is located downstream of Bent's Old Fort, Big Sandy Creek and other tributaries are sources of coarse sediment. Evidence for change in sediment character at Carlton in the past 150 years is lacking.

In 1944, John Martin Dam (Fig. 4) began affecting the amount of sediment delivered to the lower study segment. The Corps of Engineers (1973) reported an 85.7% trap efficiency for sediment reaching the dam. Above John Martin Dam, and also above the lower study segment, the Corps of Engineers (1960) calculated that 4.7 million m^3 (3800 acre-feet) of sediment per year are diverted from the river with irrigation water. This indicates that both irrigation diversions and John Martin Dam decreased the sediment load of the Arkansas River.

Figure 8 is a cross section of the point bar and floodplain at Bent's Old Fort. Between 40 and 80 meters from the channel, a natural levée had formed in the young woody vegetation. Behind the natural levée, between 80 and 200 meters from the channel, is a chute cutoff where woody vegetation is sparse. A natural levée is located at 200 m, and between 200 and 400 m the topography is flat with large cottonwood trees. Beyond 400 meters, extending to the terrace below the Fort, there are only grasses.

In general, the upper end of the cross section (250 to 700 meters) is composed of many layers of fine-grained deposits. Total thickness of the deposits is 2 to 2½ m. In a southward direction, the deposits become thicker and less numerous. Within

200 meters of the channel, they disappear altogether. Correlation lines in Figure 8 were based on the sequential order of the units.

The topographic high, at approximately 200 m from the channel, separates the active point bar from the floodplain. Pit and auger holes north of this point revealed natural levée, floodplain, and possibly crevasse-splay deposits overlying channel sands. Between 200 and 375 m from the channel, the stratigraphy appears to be transitional between gravelly chute cut-off deposits and floodplain deposits.

An antique bottle was found in Pit "C" (Fig. 8) 1.5 m below the surface. The bottle was probably manufactured between 1903 and 1923 according to an antique-bottle collector (Bass, 1977, personal communication), indicating the meander could not have enlarged part this point before 1903. This agrees with cottonwood ages and map evidence (Fig. 7) which proves that the 1926 channel was north of this point. Therefore, the bottle was deposited after 1926, as the meander enlarged to the south.

In summary, the deposits at Bent's Old Fort that are located more than 200 m from the channel are numerous thinly-bedded floodplain deposits overlying coarse channel sediment. The floodplain deposits coarsen southward to younger sands and gravels of the chute cut-off and lower point bar facies.

Figure 9 is a diagram of the floodplain topography and stratigraphy at Carlton (Fig. 4). The site is at the transition between the sinuous reach and the straight reach; meander amplitude is less than at Bent's Old Fort, and topography and stratigraphy are simpler. There are a few scattered cottonwoods in the area, but the oldest is only 13 years. The trees grow in sandy, gravelly alluvium. They are probably uprooted easily by floods, which explains the lack of older trees in the vicinity.

At the base of Pit "D" a unit of medium-sand to pebble size sediment is overlain by a unit of medium-sand to cobble size sediment. Neither unit displays bedding, but the upper one is overlain by five, thin, coarse-grained fining-upward sequences.

Conspicuous in Pit "E" is an approximately 0.6 m thick zone of salt cedar roots. Merkel and Hopkins (1957) explained that anchored shoots of salt cedars send branches upward and form dense undergrowth. Robinson (1958) noted that salt cedars greatly reduce the water carrying capacity of stream channels by increasing channel roughness. The roots prevent erosion of the banks, and the thickets promote deposition of sediment.

In summary, floodplain topography and stratigraphy at Carlton are less complex than at Bent's Old Fort, and although there are no cottonwood trees older than the last major flood, salt cedars have promoted deposition in the channel and on the floodplain.

MODELS OF RIVER METAMORPHOSIS

The first hydrologic change in the South Platte and Arkansas Rivers, during historic time, was the stabilization of discharges, owing to crop irrigation, and increases in riparian vegetation. After several seasons of irrigation, the rivers became perennial, and floodplains supported more vegetation.

The droughts after 1900, in conjunction with the decrease of sediment discharge, were also causes of channel changes (Table 3). Undoubtedly, droughts have occurred throughout the existence of the rivers. The reason for their effects on river morphology

Table 3. Data for Three Study Sites

Variable	Goodrich 1867	Goodrich 1952	Goodrich 1977	Bent's Old Fort 1870	Bent's Old Fort 1892	Bent's Old Fort 1926	Bent's Old Fort 1952	Bent's Old Fort 1977	Carlton 1870	Carlton 1892	Carlton 1926	Carlton 1952	Carlton 1977
Mean annual discharge (cms)	(Decreased 1927–1939) 1927–1939)		16.2	(Decreased 1928–1939)				6.8	(Decreased 1928–1939)				5.9
Peak discharge	(Decreased 1925–1937)			(Decreased 1924–1935)					(Decreased 1930–1941, also affected by dam)				
% silt-clay			1.22					5.01					2.85
Med. grain-size (mm/ϕ)	1.86/ −0.895[a]		0.992/ 0.012			1.27/ −0.344[a]		0.248/ 2.010			0.618/ 0.695[a]		0.928/ 0.108
Sed. sorting (ϕ)	1.915[a]		1.924			2.301[a]		0.618			1.098[a]		1.174
Vegetation	Sparse cotton-woods, no under-brush	More cottonwoods, willows and other shrubs; vegetation thicker		Large cotton-woods, little underbrush, no salt cedars		Salt cedars, cottonwoods, willows			Large cotton-woods, little underbrush, no salt cedars		Salt cedars, cottonwoods, willows		
Valley slope		.0015	.0015		.0016		.0018			.0012		.0016	
Channel slope	.0013	.0012	.0012	.0013	.0014	.0015	.0010		.0010	.0011	.0011	.0012	
Sinuosity	1.14	1.25	1.25	1.20	1.10	1.21	1.84	1.89	1.15	1.12	1.48	1.38	1.38
Wavelength (km)	Not applicable			1.74	1.22	1.35	1.24	1.22	6.82	6.71	1.74	2.01	2.01
Amplitude (km)	Not applicable			0.47	0.32	0.34	0.71	0.73	1.58	1.32	0.63	0.64	0.64
Width (m)	535	80	109	185	225	225	45	30	210	350	235	63	34
Width/depth ratio	Greater than 81		81	Greater than 17				17	Greater than 28				28
Floodplain construction	Complex infilling-island formation and attachement			Point bar formation					Simple infilling				
Channel change	Multiple-thalweg to single-thalweg			Braided to meandering channel					Multiple-thalweg to single thalweg				

[a]Historical channel material, precise age unknown.

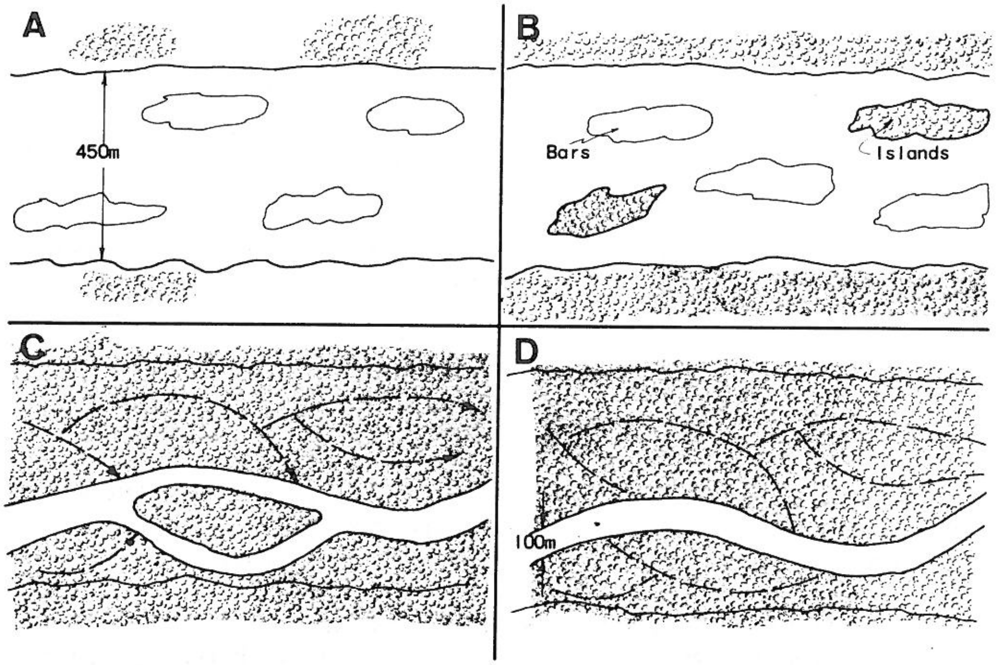

Fig. 10. Model of South Platte River metamorphosis. A—Early 1800s, discharge is intermittent, bars are transient. B—Late 1800s, discharge is perennial, vegetation is thicker on floodplain and island. C—Early 1900s, droughts allow vegetation to establish itself below mean annual high water level, bars become islands, single thalweg is dominant. D—Modern channel, islands attached to floodplain, braided patterns on floodplain are vestiges of historic channels.

in the past 100 years is due to the greater base flow caused by irrigation return flow. Before these hydrologic changes triggered an increase of woody vegetation, the banks were unprotected and the channels remained unbraided. A change to perennial flow and an increase in woody vegetation stabilized channel morphology.

Models of river metamorphosis for the three study reaches are based on channel changes, floodplain topography, and type of sedimentation as documented at three study sites. The metamorphosis in each case was controlled by sedimentologic, hydrologic, and botanical variables. Table 3 summarizes the variables for each site within the study reaches.

South Platte River

Figures 10 and 11 depict the manner of South Platte River metamorphosis, which is characterized by stream shrinkage and complex vertical accretion. The sandy basal unit (Fig. 5) which is interpreted to be the historic channel fill, is approximately the same elevation as the modern channel. The thalweg did not aggrade, but a floodplain was formed adjacent to the thalweg by island construction and channel filling. When a drought occurred, vegetation quickly colonized areas below the mean high water level of the channel (Fig. 10C). In this way, newly formed bars were stabilized and

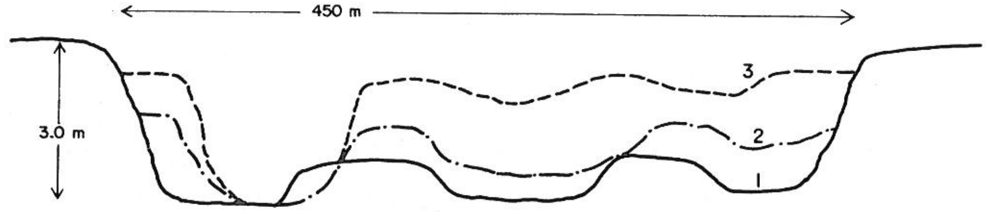

Fig. 11. Cross sections of South Platte River showing metamorphosis. Line 1—Pre-metamorphosis channel. Line 2—Transition channel. Line 3—Modern channel.

became islands. The channels, which surrounded these islands, no longer shifted because vegetation had fixed the position of banks and islands. Channel abandonment and island attachment to the floodplain followed (Fig. 10D).

Floodplain construction by the process of island formation and channel abandonment was discussed by Schumm and Lichty (1963) for the Cimarron River, by Brice (1964) for the Loup Rivers, and by Mead (1896) for the Arkansas River in eastern Kansas. Supporting evidence for this model is found in the topography and stratigraphy of the floodplain at Goodrich. The extensive sandy basal unit is the historic channel fill (Fig. 5) that is overlain by a discontinuous, but thick, silt-and-clay unit, which is interpreted as island and overbank material. The topographic

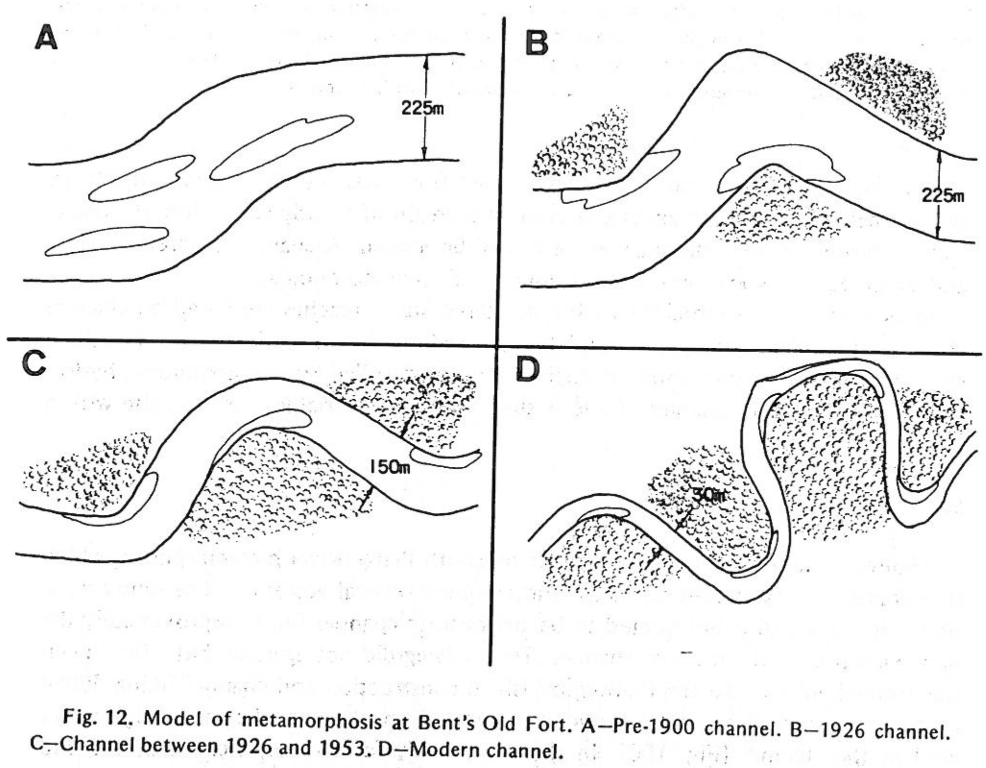

Fig. 12. Model of metamorphosis at Bent's Old Fort. A—Pre-1900 channel. B—1926 channel. C—Channel between 1926 and 1953. D—Modern channel.

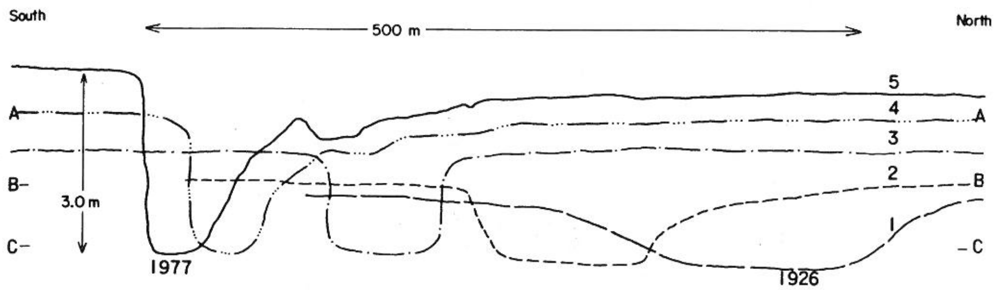

Fig. 13. Cross sections of Arkansas River at Bent's Old Fort showing metamorphosis. Line 1—1926 channel location. Lines 2, 3, and 4—Transitional channel locations. Line 5—1977 channel location. Elevation letters discussed in text.

high between 260 and 400 m (Fig. 6) was also an island. The former braided pattern can be seen on aerial photographs (Fig. 1).

The ages of the largest cottonwood trees on the floodplain indicate that the islands were being colonized by woody vegetation at least 60 years ago. This suggests that the metamorphosis began after 1900.

Arkansas River, Bent's Old Fort Reach

Figures 12 and 13 depict the manner of river metamorphosis at Bent's Old Fort on the Arkansas River. The important characteristics of this model are point-bar stabilization and meander-loop enlargement. Perennial flows, droughts, and especially dense salt-cedar growth were major factors leading to the metamorphosis. Salt cedar colonized the channel below mean high water level and stabilized the point bars during the drought of the 1930s. This process allowed meander loops to enlarge as channel width decreased.

Evidence for the model is found in channel pattern changes (Fig. 7) and in the topography and stratigraphy of the floodplain (Fig. 8). At elevation A (Fig. 13), the alluvium becomes coarser-grained toward the channel as expected; whereas, at elevation C it becomes finer-grained from right to left. The change to finer-grained sediment is the result of a change in the type of sediment transported through the reach. This change is the result of the incision of Timpas Creek (Fig. 4), a deeply incised channel that introduced a large suspended load into Arkansas River.

Arkansas River, Carlton Reach

Figures 14 and 15 are schematic diagrams of the river metamorphosis that occurred at Carlton. They depict the change from a wide, bar-braided channel with occasional large islands to a single thalweg channel. The process was one of simple vertical accretion, unlike the complex process at Goodrich where many islands were formed in the river and attached to the floodplain, but simple infilling of the channel adjacent to the thalweg appeared to be the dominant process of river metamorphosis.

The maps, aerial photographs, and field studies provide evidence for this infilling. The maps indicate few islands and Figures 1 and 3 demonstrate the absence of a

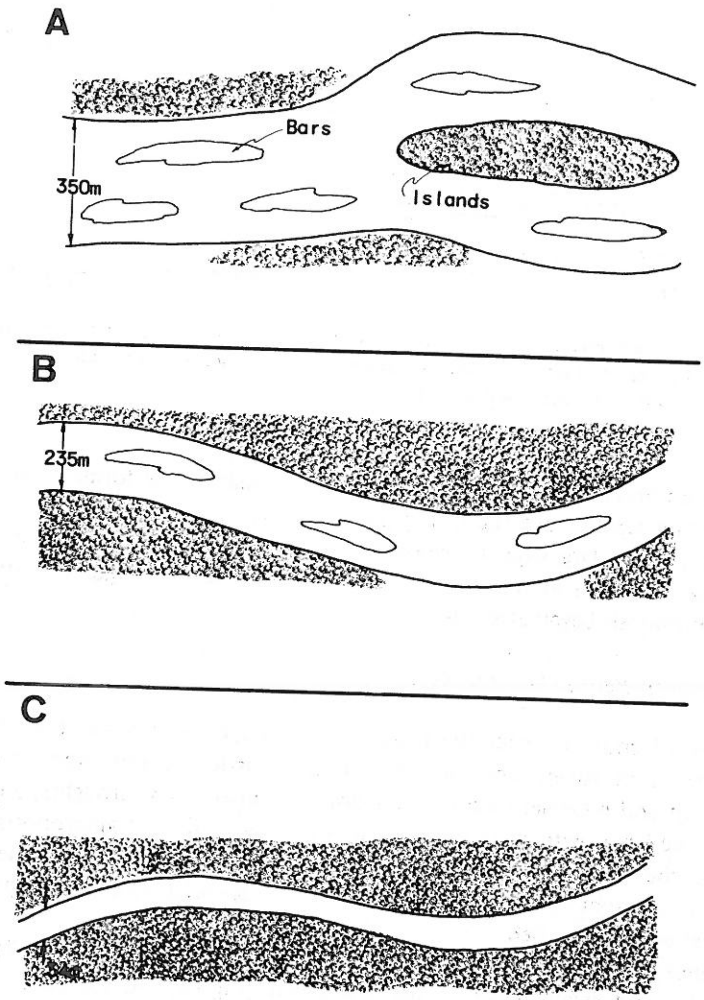

Fig. 14. Model of metamorphosis at Carlton. A—Pre-1900 channel, bar braided, few large islands, multiple thalweg. B—1926 channel, bar braided, no large islands, narrower. C—Modern channel, single thalweg.

braided pattern on the floodplain at Carlton. Pits in the floodplain revealed massive sand deposits and many salt cedar roots. The salt cedar decreased the velocity of the water by increasing channel roughness, which resulted in accumulation of sediment.

The final product of the Carlton metamorphism is not exceptionally stable. The absence of cottonwood trees older than the last major flood indicates cottonwoods growing in the coarse grained alluvium, which can be washed out. As a result, the channel may widen following a single major flood.

SUMMARY AND CONCLUSIONS

The South Platte and Arkansas Rivers in eastern Colorado have metamorphosed during the last 150 years owing to hydrologic and sediment changes produced by

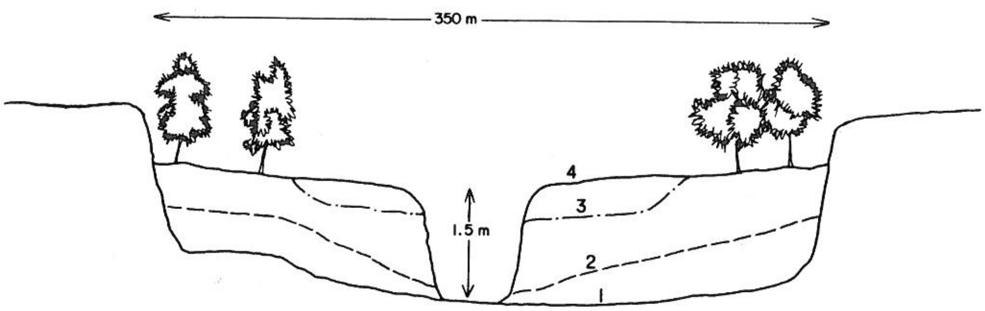

Fig. 15. Cross sections of Arkansas River at Carlton showing metamorphosis. Line 1—Pre-metamorphosis channel. Line 2—Transitional channel. Line 3—Base of thin coarse grained deposits. Line 4—Modern channel.

man and by climatic fluctuations. The two rivers responded differently to changes in similar external variables.

At Bent's Old Fort, on the Arkansas River, the channel changed from braided to meandering (Fig. 12). At Goodrich, on the South Platte, and Carlton, on the Arkansas, the channels changed from multiple-thalweg channels to single-thalweg channels without a large increase in sinuosity (Figs. 10 and 14). At Goodrich, the process included an intermediate step of island construction and attachment to the floodplain, but at Carlton, a single thalweg formed or the adjacent channels were filled by vertical accretion.

The morphologic changes can be attributed partly to decreases in water and sediment discharge. Because irrigation water is also diverted from the South Platte River, it is reasonable to assume that it has also experienced a decrease in sediment load. Although irrigation began in the 1860s, the major morphologic changes did not occur until the turn of the century. The droughts after 1900, in conjunction with the decrease in sediment discharge and rise in the water table, were the major causes of the channel changes.

Differences in type and density of vegetation may also affect the types of metamorphosis that occured at Goodrich and at Carlton. Dense thickets of salt cedar, which line the river at Carlton, are absent at Goodrich. At Carlton during the drought years, salt cedar colonized the channel, thereby increasing roughness and, therefore, deposition adjacent to the thalweg. Because salt cedars were absent at Goodrich, channel change and floodplain construction was a complex process of vertical accretion with island formation and attachment. Large islands existed in the Arkansas River near Carlton before 1900 (Fig. 7), but they did not play a role in river metamorphosis.

When the South Platte and Arkansas Rivers changed from intermittent to perennial flow due to irrigation return flow, the change was analogous to a climatic change. Vegetation became denser and flow became perennial. River metamorphosis in response to development of perennial flow can also be used to explain changes in Pleistocene and Holocene channels. Most explanations of river response depend on altered flood peaks or changes in mean annual discharge; but in this case, a change in discharge frequency resulted in major channel adjustments.

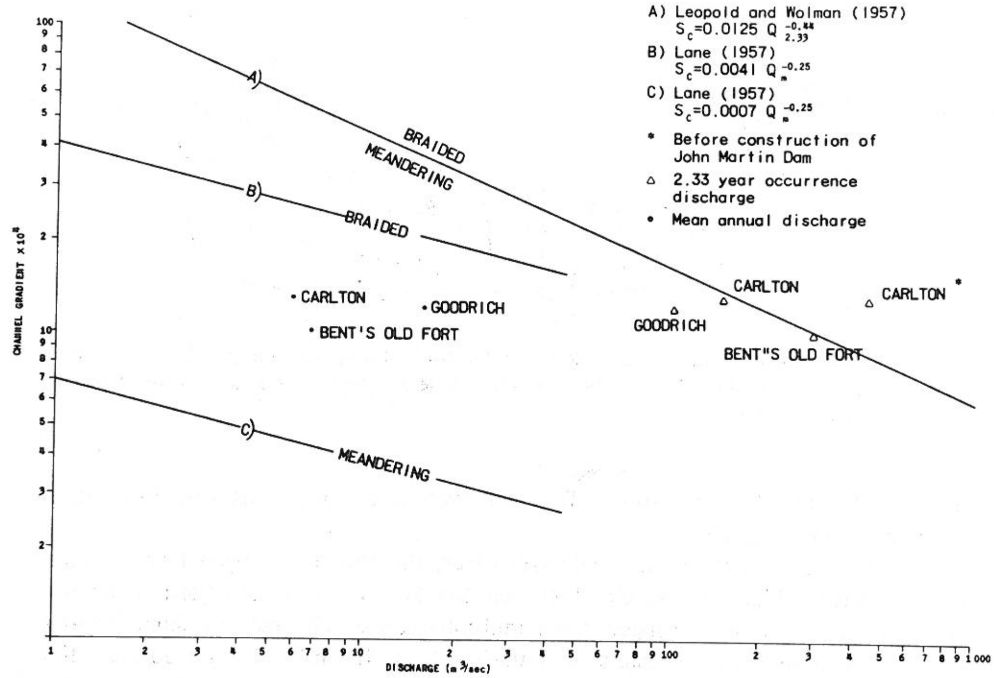

Fig. 16. Channel slope and discharge as related to channel pattern.

Discharge may affect channels in a different way, but it alone cannot explain the variation in channel patterns and dimensions for rivers of similar discharges. For instance, the mean annual discharge at Bent's Old Fort and at Carlton is nearly the same, yet the channels exhibit two distinctly different patterns and types of metamorphosis (i.e., braided to meandering at the Bent's Old Fort reach, and multiple thalweg to single thalweg at the Carlson Reach).

Experimental (Schumm and Khan, 1972) and field observations (Schumm, 1979) suggest that some rivers metamorphose because they are morphologically close to a geomorphic threshold, when a slight change in hydrology, hydraulics or sediment load can cause a dramatic change of channel morphology.

Leopold and Wolman (1957) and Lane (1957) showed that channel slope and discharge are related to channel pattern and they defined threshold conditions separating these patterns (Fig. 16). Considering mean annual discharge, the three sites plot between lines B and C that Lane derived for braided and meandering patterns (Fig. 16). The channels at Goodrich and Carlton are closer to the braided line, whereas the channel at Bent's Old Fort is closer to the meandering line.

Plotted points for the 2.33 year recurrence discharge lie close to the threshold line A (Fig. 16) of Leopold and Wolman. Before construction of John Martin Dam, the channel at Carlton was located in the braided region of the graph; today, it is located in the meandering region. The channel at Goodrich plots in the meandering region, whereas the channel at Bent's Old Fort lies on the threshold line. The location

Table 4. Comparison of Suspended Loads-Arkansas and South Platte Rivers[a]

Station	Annual suspended load (tons)	Annual runoff (Ac-Ft)	Annual rate (t/Ac-Ft)
South Platte			
Sublette	729,000	370,000	1.97
Ft. Morgan	1,827,000	361,000	5.06
Arkansas			
La Junta	3,101,000	261,000	11.88
Caddoa	2,218,000	312,000	7.11

[a]From A. Alkin, 1978, Soil Conservation Service, written communication.

of these points suggests that these reaches are unstable and may shift from one pattern to another with a small change in an independent variable. Clearly the high discharges of the past would have placed the three reaches in the braided zone of the Leopold-Wolman relation.

The general similarity of the positions of the three reaches, as shown in Figure 16, suggests that the channels were susceptible to change, and that a major change of discharge or sediment load could produce significant channel responses. This was certainly the case in the Bent's Old Fort reach, where the influx of suspended-sediment from Timpas Creek caused meandering. This type of channel change has been observed experimentally (Schumm and Khan, 1972).

A suspended-load channel with a high percentage of silt and clay in the channel will have a low width-depth ratio and in most cases a higher sinuosity (Schumm, 1960). This was found to be true for the reaches investigated (Table 3).

Table 4 is a comparison of suspended sediment loads of the two rivers. The Arkansas River carries more suspended sediment per acre-foot of runoff than the South Platte River. The value at Caddoa might be higher but it is located immediately downstream of John Martin Dam. These data support the conclusion that the South Platte River is a bed-load stream, whereas the Arkansas River is a mixed-load stream at Bent's Old Fort and a mixed-load or bed-load stream at Carlton. All else being the same, the South Platte River should have a larger width-depth ratio and be less sinuous than the Arkansas River.

The finest sediments are found in the Bent's Old Fort reach (Tables 1, 2, 3, and 4). The lowest M values were recorded on the South Platte River, and the Carlton reach was intermediate between the two. Since the value at Carlton was closer to values from the South Platte River than it was to the value at Bent's Old Fort reach, it should be expected that the types of river metamorphosis and floodplain construction at Carlton and Goodrich should be different from the types at Bent's Old Fort. When flood peaks are reduced and base flow is increased, a braided stream having a high silt and clay load will metamorphose to a meandering channel, and floodplain construction by point bar development can be expected. However, a braided stream having a low silt and clay load will metamorphose by adopting a single thalweg of low sinuosity, and flood plain construction by vertical accretion should be expected.

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