Chapter 7. Euro-American Beaver Trapping and Its Long-Term Impact on Drainage Network Form and Function, Water Abundance, Delivery, and System Stability

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Introduction

Euro-American (EA) beaver trapping was a regional and watershed-scale disturbance that occurred across the North American continent. This concentrated removal of beavers altered drainages by creating thousands of localized base-level drops as beaver dams failed and were not repaired. These base-level drops led to the development of channels as ponds drained and water eroded the fine sediment trapped behind the dams (Dobyns 1981; Fouty 1996, 2003; Parker et al. 1985). The speed at which drainages transformed from beaver-dominated to channel-dominated varied as a function of climate, upland and riparian vegetation, and the subsequent land uses. As the drainage network pattern changed, flood magnitudes and frequencies increased and base flows decreased, creating stream systems much more sensitive to climatic variability.

In most places, trapping predates EA settlement. The one exception is New England in the 1600s where settlement and trapping co-existed in time. The journals from this time period provide intriguing but limited references to vegetative and ecological changes as a result of beaver removal (Cronon 1983). This limited historic documentation of system response to the widespread removal of beavers resulted in our missing the significance of early EA beaver trapping on drainage network development, water abundance, delivery, and system stability. However, the abundant and high quality written records left by the early General Land Office (GLO) surveyors and scientific and military expeditions of their observations of the Southwest and Intermountain West hold promise because they entered these areas only 10 to 30 years post-trapping. Their observations when combined with later research suggest that EA trapping and grazing, though temporally and spatially separated, led to extensive drainage network development in the West and an increase in the sensitivity of stream ecosystems to climate variability. This transformation pre-dates the installation of stream gages and the data collection that forms the basis of our understanding of hydraulic geometry, channel form, and fluvial processes. Consequently, current fluvial geomorphic relationships and our understanding of stream sensitivity to climatic variability reflect highly disturbed watersheds and ecosystems, not healthy intact systems. Without realizing it, the GLO surveyors and the early military and scientific expeditions had captured not virgin territory, but a landscape in transition.

Using current research and historic observations, I developed a conceptual model describing the geomorphic and hydrologic response of a drainage basin to the entry of beavers and then their removal or abandonment (Fouty 2003). The conceptual model is similar in structure to Cooke and Reeves' (1976) deductive model of arroyo formation in the Southwest in that both models examine the hydrologic and geomorphic response of streams to EA disturbances. Cooke and Reeves (1976) focused on post-settlement EA disturbances such as livestock grazing, logging, agriculture, and road building. The conceptual model presented here steps further back in time to examine the impact of EA beaver trapping on drainage systems.

Currently, the most visible impact of beavers would occur on first- through fourth-order streams because beavers can build their dams across these stream sizes (Naiman et al. 1986; 1988) and thus have a direct effect on the physical appearance and hydrologic behavior of the drainage network in these areas. However, historically beaver dams would have occurred on higher order streams. The current widths and depths we see for larger order streams is an artifact of and response to the magnitude and abundance of disturbances that have occurred. Prior to trapping and subsequent EA disturbances, streams in many places were anabranching, narrower and had high stream-valley floor connectivity (Sedell and Froggatt 1984; Walter and Merritts 2008).

With the conceptual model as the framework for analysis, this paper then (1) explores why EA beaver trapping as a major disturbance was missed and absent from the discipline of fluvial geomorphology until recently, (2) reexamines the early observations in the Southwest and Intermountain West in the context of EA beaver trapping, and (3) concludes with a brief discussion of Leopold and Maddock's (1953) hydraulic geometry relationships, one of the foundations of fluvial geomorphology. When these relationships are put into their historic disturbance context, one that includes beaver trapping and later land uses, the magnitude and longevity of the impact of EA beaver trapping on drainage networks, water abundance, and system resiliency becomes clear.

Conceptual Model Part 1: Watershed Response to Long-Term Beaver Presence

The fluvial processes and sequence of events that occur when beavers enter a drainage area and establish a long-term stable presence are shown in figure 19. An excellent discussion of the changes in more detail can be found in Naiman et al. (1988) and so are only briefly discussed here. Changes begin with dam building and foraging for vegetation around the pond area. As beaver dam complexes expand, changes occur to (1) water abundance and vegetation, (2) local and downstream hydrographs, and (3) the character of the drainage network. In figure 19, the local effects are broken down into low-energy environments and high-energy environments. The distinction is made because dams in low-energy environments tend to be stable, allowing wetlands to form and evolve into meadows (if sediment is abundant), while dams in high-energy environments (i.e., steeper gradient streams, higher discharge streams) are more prone to periodic failure and wetlands and meadows less likely to form (Meentemeyer and Butler 1999).

In terms of conceptual models, there are key differences between beaver-dominated and channel-dominated systems. In beaver-dominated systems, stream channels are interrupted by dams that develop ponds across the channel and valley floor and lead to the creation of wetlands. In contrast, the conceptual model of a channelized drainage network is visualized as a set of interconnected channels "where physical variables present a continuous gradient of physical conditions from the headwaters to the mouth" (Naiman et al. 1986). This conceptual model of a watershed of interconnected channels is implied in the hydraulic geometry relationships of Leopold and Maddock (1953) and other researchers

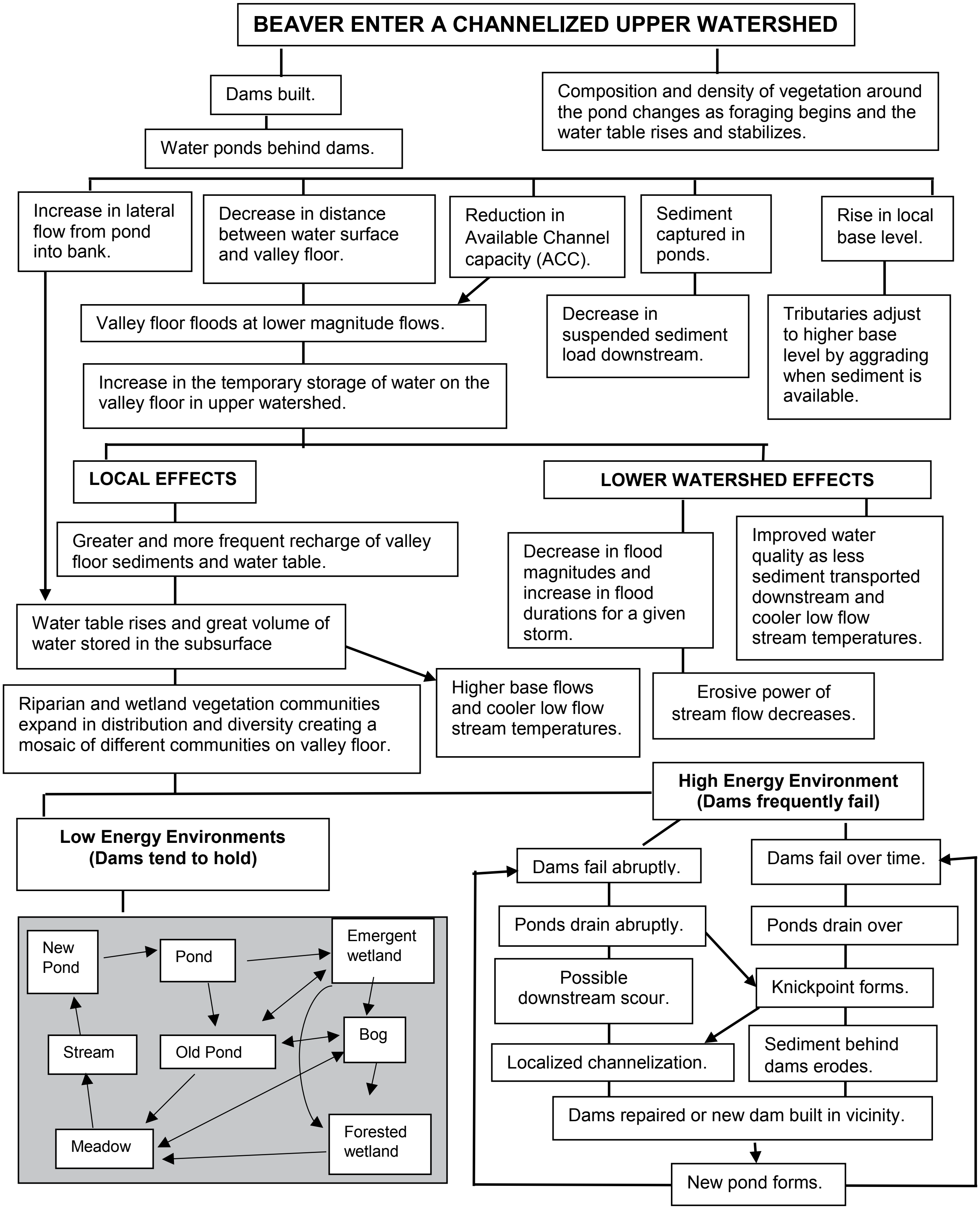

Figure 19—Conceptual model of how beavers influence fluvial systems at the watershed scale (source: Fouty 2003; portion in the shaded box is from Naiman et al. 1998).

(Knighton 1998). It is also an assumption in the discharge-drainage area relationships that have been developed and used to guide and inform stream restoration efforts.

The most visible change once beaver dams are built is the increase in the amount of surface water stored within a given section of stream, but the increase extends beyond surface water to include groundwater. I modeled the potential increase in the total amount of water that would be stored in a 29 acre meadow with 0.76 miles of stream, and available to the river, using a point-in-time volume estimate of the amount of water held in the channel during the summer as baseline conditions. The reach occurs on Camp Creek, a tributary to the North Fork Burnt River (NFBR), located in eastern Oregon. The goal was to predict potential water-related benefits if beaver returned to the creek. Beavers are currently present in the NFBR but not in Camp Creek, though past signs of their presence exist and beaver habitat restoration efforts are underway. Commercial and recreational trapping currently occur in the NFBR watershed and the area is a mix of public and private land.

The calculations used existing cross-section data, information about summer water levels, an average bank height of 5 ft, and expected soil types (silt loam and sandy loam). The meadow was assumed to be one or the other soil type resulting in a range in values. Using information from Dunne and Leopold (1978), the soil porosity values used were 0.46 for silt loam and 0.44 for sandy loam and the field capacity values used were 0.31 for silt loam and 0.15 for sandy loam. These values were used to estimate the amount of groundwater that could be stored in the meadow under saturated conditions and capable of draining freely to the river. The calculations assumed that the dam heights equaled the average bank height.

Without beaver dams (baseline condition), the estimate of in-channel surface water was 0.4 acre-ft for the 0.76 miles of stream. Summer contributions from groundwater to base flows are limited because the channel is incised and over-wide. With beaver dams, the volume of in-channel surface water would increase from 0.4 acre-ft to 9 acre-ft. A saturated meadow could contribute an additional 22 acre-ft (if silt loam) to 42 acre-ft (if sandy loam) of groundwater to the river, contributing to summer baseflows. If the dams extended across the valley floor and were a foot tall, an additional 29 acre-ft of surface water would be held in temporary storage. When all the values are totaled, the amount of water that could be stored within this 29-acre meadow and available to drain freely into Camp Creek if beaver dams were present increases from 0.4 to as much as 80 acre-ft of water.

A landscape-scale example of actual change in response to beavers expanding their range occurred between 1940 and 1986 on the Kabetogama Peninsula, a 17.4 mile^2 area in Minnesota. Using aerial photos, Naiman et al. (1988) counted 71 beaver dams in 1940 and 835 dams in 1986. The cover types were lumped into four categories (forest, wet, moist, ponds). In 1940, acres in the moist, wet, and pond categories were 640. By 1986 the number had increased to 9,308 acres with a large portion of that change achieved by 1961. Ponds increased from 40 acres to 3,388 acres reflecting large increases in surface water. The moist and wet categories increased from 600 to 5,921 acres reflecting a large increase in groundwater stored. Other examples exist within the literature that capture the water storing capability of beavers (Beedle 1991; Hood and Bayley 2008; Demmer and Beschta 2008), leaving little doubt about the ability of abundant beaver populations to effectively help mitigate the effects of climate variability.

Reductions in Downstream Flood Magnitudes

Beaver ponds have long been credited with reducing flood magnitudes and stream power through pond storage, valley-floor storage, or both (Dobyns 1981; Naiman et al. 1988; Parker et al. 1985)—assumptions that have been "based primarily on qualitative observations in the literature from the first half of the century" (Meentemeyer and Butler 1999). Actual studies quantifying the influence of beavers on flood magnitudes are few, have focused on small headwater streams, and have only considered the role of pond storage in flood peak reductions. Burns and McDonnell (1998) compared two stream hydrographs. One hydrograph captured flows in a 102 acre drainage containing a perennial stream and a single 3.2 acre beaver pond at its downstream end. The other hydrograph captured flows for a 151.2 acre watershed containing an ephemeral stream and no beaver pond. They found that the single pond provided minimal retention during several large runoff events. Beedle (1991) explored how storm hydrographs responded to increasing amounts of pond storage as the size and numbers of ponds in series increased. The drainages studied were 1,532 acres or less and his maximum pond size was 1.48 acres. He found that the amount of reductions varied with storm size, pond size, pond numbers, and available storage capacity of the ponds prior to the flow event.

A single full beaver pond was found to theoretically reduce peak flows by no more than 5.3 percent regardless of the return interval or watershed size. The shape of the outflow hydrographs were the same as the inflow hydrographs, with only a 10 or 15 minute delay in the time to peak and slightly increased duration. Reductions in peak flows became increasingly large as the number of ponds in a series increased. Five large-sized beaver ponds in series reduced the storm peak flow by 14 percent for a 2-year event, but only 4 percent for a 50-year event (Beedle 1991).

However, the greater contribution of in-channel ponds as it pertains to reducing flood magnitudes is that they reduce the available channel capacity (ACC). This causes streams to overtop their stream banks at lower flows allowing flood waters to access the valley-floor where temporary flood storage is greater.

The degree to which overbank flooding decreases flood magnitudes and increases flood durations varies as a function of valley-floor roughness (Campbell et al. 1972; Leopold and Maddock 1954; Shankman and Pugh 1992), the amount of storage area (Campbell et al. 1972; Osterkamp and Costa 1987), and the location of unmodified sections of river with respect to the flood wave (Campbell et al. 1972; Hillman 1998). The mix of channelized and nonchannelized reaches results in a discontinuity in flood magnitudes, durations, and frequencies as a flow moves downstream. Some areas will experience increased flooding while others (e.g., downstream of a wetland) will show minimal changes for the same precipitation or dam-bursting event (Campbell et al. 1972; Hillman 1998).

Reductions of flood magnitudes as a result of valley-floor storage in systems where the streams are hydrologically connected to their valley floors but without beavers have been documented by a number of researchers. Osterkamp and Costa (1987) estimated water depths at three valley cross-sections on Plum Creek in Colorado, which drains 328.2 miles^2. During a 900 to 1,600-year recurrence interval, flood water depths averaged from 7.9 to 9.5 ft but were as great as 19 ft. Dunne and Leopold (1978) examined runoff from four large drainage basins ranging in size from 7,411 to 203,000 miles^2. They found that the channel and valley floor stored 57 to 80 percent of the runoff generated by large storms. Campbell et al. (1972) used two flood-routing methods to determine the effect of channel straightening on flood magnitudes, durations, and attenuation of the flood peak for 58 miles of the Boyer River in Tennessee. The river drains 1,188 miles^2. Channel straightening and the building of dikes increased discharge downstream by limiting access to the valley floor and increasing the stream gradient. In contrast, under partial straightening they found that the unmodified sections of the stream substantially reduced the magnitude of flood peaks because the flood waters overflowed onto the valley floor. The floodplain in the unmodified section averaged 1.3 miles wide.

Campbell et al. (1972) reported the following results of their modeling: "The unmodified reach, even though short, provides tremendous storage, which can nullify the effects produced by the upstream straightening. As indicated in figure 8c, 16 miles of unmodified river reduced the increase in peak discharge from 90 percent to 15 pecent for the condition of high flood plain roughness coefficient. The increase in peak discharge at section 30 [the most downstream section and below the unmodified section] is 35 percent with high n [0.10] and 30 percent with low n [0.04] as compared with 190 percent and 90 percent respectively for complete straightening."

A smaller scale example comes from Rocky Creek in central Alberta. It drains an area of 4,621 acres. Hillman (1998) observed the influence of a 222.4-acre wetland on downstream flood flows after a beaver dam failed. The wetland contained a sedge meadow, willows, a small lake, and several beaver ponds. By the time the flood waters had passed through the wetland and reached the main gage, about 4 miles downstream of the dam failure, the flood peak was only 6 percent of the peak estimated to have entered the wetland. He concluded that wetlands, especially when large, are very effective at regulating high flows, even more so than beaver ponds because the dams often wash out during high floods.

These examples show that valley-floor storage, beaver ponds, and wetlands can significantly reduce flood peaks at all scales of drainage area and storm size. As such, the loss of wetlands and beaver ponds and the severing of stream-valley floor hydrologic connections has the reverse effect, increasing flood peaks for all sizes of storms and drainage areas. Nowhere has the impact of lost storage potential been more frequently on display than in the Mississippi River Basin. Hey and Philippi (1995) estimate that beaver ponds and wetlands historically made up 11 percent and 10 percent respectively of the 450 million acres of the Missouri and Upper Mississippi River Basins. They currently make up 1 percent and 4 percent. The reduction of these features, along with the development of a channelized drainage network and levee system, has led to increases in the magnitude and frequency of downstream flooding with large economic and social costs.

Conceptual Model Part 2: Watershed Response to Beaver Trapping After a Long-Term Presence

The fluvial processes and sequence of events that occur when beavers are removed after a long-term presence, but prior to another large-scale disturbance, are shown in figure 20. Decreases or elimination of beavers from drainages means that dam failures are not repaired. The lack of dam maintenance at multiple sites within a drainage and across a region sets in motion changes that allow the channels to expand beyond the point of

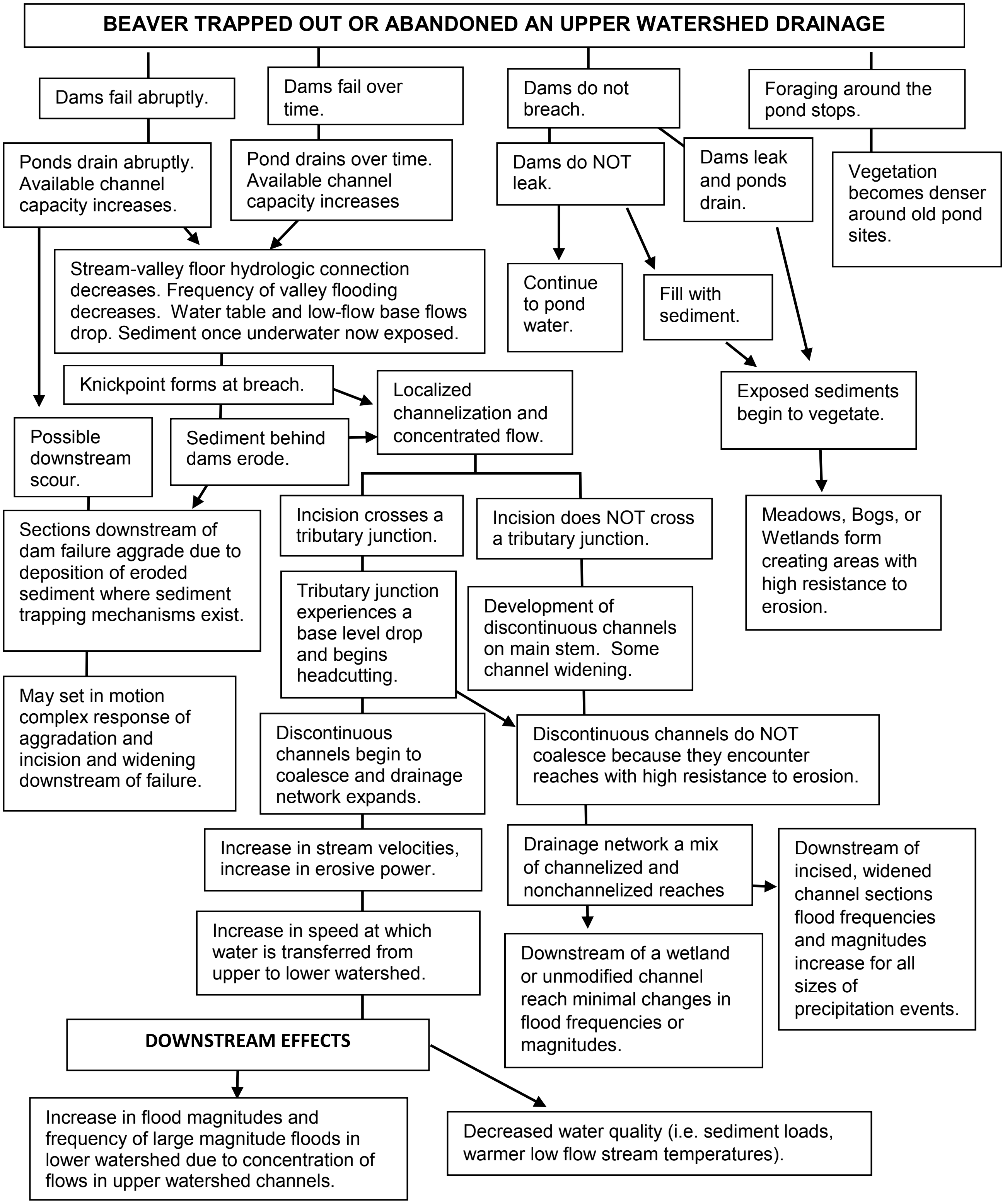

Figure 20–Conceptual model of how beaver trapping or site abandonment influence fluvial systems (source: Fouty 2003).

dam failure. With failures, (1) ponds drain and sediment erodes, (2) available channel capacity (ACC) increases, (3) local base-levels drop, (4) knickpoints form, and (5) the stream-valley floor hydrologic connection becomes increasingly disconnected.

The impact of beaver trapping and subsequent dam failures on ACC and thus the stream-valley floor hydrologic connection was captured at Price Creek in southwestern Montana (Fouty 2003). Fourteen monumented cross-sections were established in 1995. Twelve occurred inside a cattle exclosure that contained beaver dams. Two occurred downstream of the exclosure in a section without beaver dams. In 1995, the percent ACC at the dam-controlled cross-sections ranged from 0 percent (channel full) to 62 percent depending on dam integrity (table 2), which was already varying as a result of beaver being trapped out between 1994 and 1995. By 1998 all dams were failing or gone and the percent ACC had increased at all sites.

Table 2—Changes in available channel capacity (ACC) as a result of dam failure and pond drainage, Price Creek, Montana. Cross-sections 17 and 18 were downstream of the beaver dam controlled reaches (source: Fouty 2003.)

Cross-section number	% Available channel capacity[a]		Dominant reason for the change in available channel capacity	Distance upstream of a beaver dam (ft) and timing of dam failure
	1995	1998		
19	0	69	Pond drains	115 ft. Begins breaching post 1995 but still exerting some influence in 1997 and 1998.
20	0	84	Pond drains and sediment erodes	30 ft. Begins breaching post 1997 but still exerting some influence in 1998.
21	38	81	Pond drains	39 ft. Begins breaching post 1997 but still exerting some influence in 1998.
22	39	91	Pond drains	52 ft. Begins breaching post 1997 and gone by 1998.
23	17	68	Pond drains and sediment erodes	49 ft. Begins breaching post 1997 but still exerting some influence in 1998.
24	26	72	Pond drains and sediment erodes	10 ft. Begins breaching post 1995. Completely breached by 1998.
25	66	84	Pond drains	62 ft. Intact in 1997, gone by 1998.
26	63	80	Pond drains	89 ft. Begins breaching post-1997 but still exerting some influence by 1998.
27	35	71	Pond drains	36 ft. Begins breaching post-1997 but still exerting some influence by 1998.
28	62	84	Pond drains	72 ft. Begins breaching post 1995 but still exerting influence in 1997 and 1998. Below this dam was a submerged dam acted as a base-level control.
29	62	94	Pond drains and sediment erodes	10 ft. Begins breaching post 1995. Gone by 1998.
30	69	95	Pond drains and sediment erodes	10 ft. Begins breaching post 1995. Some influence still in 1997 but gone by 1998.
No beaver dam influence				
17	94	94	Minimal changes in sediment or water levels	n/a
18	87	89	Minimal changes in sediment or water levels	n/a

[a] % Available channel capacity = (1-(water XS area/channel XS area)) *100.

Changes in ACC between 1995 and 1998 inside the cattle exclosure varied as a function of proximity to a dam, dam integrity, and the length of time the dam had been in place prior to the building of upstream dams (Fouty 2003). ACC increased at all 12 cross-sections. Seven cross-sections had increases due to pond drainage, and five cross-sections due to sediment erosion and pond drainage. In contrast, the ACC at the two downstream cross-sections (17, 18) changed very little despite the large influx of sediment from upstream sites as dams failed and the sediment previously trapped behind them eroded. The lack of sediment trapping mechanisms at these two cross-sections resulted in sediment moving through the system as suspended load, giving the appearance of a sediment-starved system rather than one simply lacking sediment trapping mechanisms.

Unlike Price Creek where repeated beaver trapping has prevented the development of wetlands, streams with a long-term beaver presence and abundant sediment inputs would in time develop complex wetland vegetation communities (Johnston and Naiman 1990). Post-trapping but in the absence of another disturbance, these well-established wetlands would persist after the loss of beavers and impede the headward migration of the knickpoints initiated when the dams failed. Their location, characteristics, and stability would prevent the channels from coalescing into a single interconnected system. The resulting drainage pattern would be one in which channelized reaches are spatially separated by wetlands. The hydrologic impact of this drainage pattern would be a discontinuity in flow magnitudes and durations, similar to that described by Campbell et al. (1972) and Hillman (1998).

The effectiveness of the wetlands at impeding channel development comes from (1) their enhanced roughness that reduces flow velocities (Cooke and Reeves 1976; Hendrickson and Minckley 1984), (2) temporary storage potential that reduces flood peaks (Campbell et al. 1972; Dunne and Leopold 1978; Hillman 1998; Osterkamp and Costa 1987), and (3) their enhanced subsurface cohesion (Cooke and Reeves 1976; Finch et al. 2003; Hendrickson and Minckley 1984; Smith 1976). If, on the other hand, the wetlands develop channels or are eliminated by human activity, the drainage pattern becomes increasingly channelized (fig. 20). Examples of the amount and speed at which channelization can occur are found in table 3.

As a drainage becomes channelized, vegetation shifts from water-dependent to drought-tolerant species. This shift occurs as a result of decreased soil moisture. As a channel incises, widens, or both, the increased ACC leads to a reduction in the frequency of valley-floor flooding (Campbell et al. 1972; Schumm et al. 1984; Shankman and Pugh 1992) and enhances the flow of groundwater toward the channel by steepening the hydraulic gradient between the water table and stream (Knighton 1998 referencing Dunne 1980, 1990). The result is a lowering of the water table.

The speed at which vegetation changes varies as a function of climate, land use, incision depth, groundwater depth, subsurface stratigraphy, and vegetation requirements (Cooke and Reeves 1976). In areas where precipitation is distributed throughout the growing season, it may partially compensate for a decline in water tables if its abundance and distribution are sufficient to maintain soil moisture levels. In areas where precipitation is strongly seasonal, declines in water tables are not compensated for by precipitation, and vegetation responds more quickly to channelization and the lowering of the water table (Bryan 1928b). The speed at which vegetative communities

Table 3—Examples of the speed at which channelization occurs, and the depth, width, and length of the channelization when known (source: Fouty 2003.)

Location	Dates	Type and amount of change	Time interval	Source
Rio Salado, NM	Between 1882 and 1918	Channel widens from 11.88 to 48.84 ft wide to 330.1 to 550 ft wide.	<36 years	Bryan 1927
Felipe Gilbert Creek, NM	One storm event	Channel headcuts for a distance of 40 to 75 ft.	1 day	Bryan 1927
Whitewater Draw, AZ	The rainy season in 1910	Channel headcuts for a distance of 0.25 miles.	Up to a couple of months	Cooke and Reeves 1976
Kanab Creek, UT	Between 1883 and 1885	Channel incises 60 ft and widens nearly 70 ft for a distance of 15 miles.	<2 years	Gregory 1917
Walker Creek, AZ	Between 1894 and 1913	Channel incises 80 ft deep.	<19 years	Gregory 1917
Chinle Creek, AZ	Between 1894 and 1913	Channel incises 100 ft deep.	<19 years	Gregory 1917
Mountain Meadows, UT	1884 – in one series of storms	Channel incises into what was once a wet meadow during a series of storms and continued to widen after 1884. Gullies fingering out to nearly all parts of meadow. No numbers given.	Up to one month for initial incisions	Cottam and Stewart 1940
Crane Creek, OR	Between 1925 and 1930	Channel incises to a depth of 10 ft.	5 years	Schaffer 1941
Santa Cruz River near Tucson, AZ	Between Aug 5 and 9, 1890	Channel incises some unknown depth for 1.5 miles between August 5 and 7. Between August 7 and 9 channel begins to fork and headcut in multiple directions.	4 days	Cooke and Reeves 1976 (p. 51)
Sonoita Creek, AZ	Between 1891 and 1912	Channel incises 18 to 20 ft deep and widens to 250 ft.	<21 years	Bryan 1928b
Gila River near Safford, AZ	Between 1905 and 1917	Channel widens from an average of less than 330 to 2000 ft for about 45 miles.	<12 years	Burkham 1972
Cimarron River in southwestern Kansas	Between 1874 and 1939	Channel widens from average of 50 to 1200 ft for about 175 miles.	<65 years	Schumm and Lichty 1963
Rio Puerco, NM (between mouth and Cabezon)	Between about 1885 and 1892	Channel incises and the incision migrates upstream for 110 miles Discontinuous incision existed prior to 1885 and this may have facilitated rapid headward migration of the incision.	<7 years	Bryan 1928a
Douglas Creek, CO (East Fork)	Between 1882 and 1900	Channel has incised 16.4 ft.	<18 years	Womack and Schumm 1977
Wolf River near Memphis, TN	Between 1964 and 1999	Channel incises migrates upstream for 10.6 miles. Headcutting is episodic in nature with an average rate of headward migration of 0.37 miles/yr. Some areas have had a 19.7 ft drop in bed level and the channel has widened to twice its original width.	<35 years	Wiens 2001
Price Creek, MT	1995 and 1998	Channel incises 0 to 2.6 ft deep for sites less than 50 ft upstream of beaver dams as a result of dam failures.	1 to 3 years	Fouty 2003
Obion River, TN	Post 1960s	Channel has undergone headward migration of knickpoints as much as 0.62 miles/yr and channel widening as much as 3.28 ft/yr due to channelization of the river by U.S. Army Corps of Engineers in the 1960s.	1 year	Shankman and Pugh 1992

change further accelerates where land uses increase runoff rates, decrease infiltration rates, surface roughness, and stream-bank vegetation, and damage soil structure. A self-enhancing feedback loop is triggered as increased runoff and loss of bank stability and floodplain roughness facilitate channel enlargement during high flows furthering a lowering of the water table and a shift to more drought tolerant, less densely rooted vegetation. This change to more drought-tolerant species in turn sets another feedback loop in motion by decreasing the water-holding capability of the soil as below-ground root biomass declines (Fitch et al. 2003). In the examples presented in table 4, major changes occurred between 4 to less than 50 years, the time frames constrained by the next observation.

The conceptual model represented by figures 19 and 20 is the backdrop for the remaining sections that explore why beaver trapping as a regional EA disturbance, and beavers as a major component of stream systems, were missed by early researchers and remained absent from the discipline of fluvial geomorphology until recently. This chapter concludes with a discussion of how adding beavers and EA beaver trapping back into the story of EA disturbances changes the discipline of fluvial geomorphology and current stream restoration efforts.

Table 4—Examples of the speed and character of vegetation changes as a result of channel incision. Unless beaver trapping or area abandonment is explicitly mentioned, the cause of the incision is Euro-American settlement activities (source: Fouty 2003.)

Location	Time interval	Vegetation change	Total time	Source
Santa Cruz River near Tucson	1880 to 1928	From area covered by sacaton grass with groves of mesquite and swampy areas of tule (bulrushes) prior to 1880 to dense mesquite forest by 1928. Arroyo forms in 1880.	Less than 48 years	Bryan 1928b
Sonoita River of Sonora	pre-Aug 6, 1891, to 1928	From swampy area prior to August 6, 1891, to a dense mesquite forest by 1928. Arroyo forms in August 6, 1891.	Less than 37 years	Bryan 1928b
Yancy Meadows, Yellowstone NP	1903 or 1904 to 1921	Beavers began to desert area in 1903 or 1904. By 1912 the colony was abandoned. Changes from ponds to well-formed meadows to solid ground by 1921 with little evidence of the earlier beaver ponds.	17 or 18 years	Warren 1926
Crane Creek, OR	1925 to 1936	Beavers trapped out in 1924. Channel incises in 1925 and vegetation changes from meadows of “stirrup-high native” grasses subirrigated by beaver ponds to meadows nearly gone, with clumps of new sagebrush and sparse remnants of the original grasses by 1936.	11 years	Schaffer 1941
Near Little Summit Ranger Station area, OR	1925 to 1929	Area was formerly full of beavers, but the last appear trapped out by 1925. “From that date to 1929 (4 years) the old ditch and the entire meadow were fast becoming a dust bed. During 1928 and 1929 no water ran out at the lower end of the station”	4 years	Bailey 1936
Mountain Meadows, southern UT	1884 to sometime prior to 1900	Channel incises into what was once a wet meadow during a series of storms and continues to widen since 1884. Gullies fingering out to nearly all parts of meadow. Shift in vegetation from a wet wiregrass meadow surrounded by numerous springs and a dry grass meadow as meadows drain to desert shrub.	< 16 years	Cottam and Stewart 1940

The Geographies of Euro-American Beaver Trapping, General Land Office Surveys, and Early Expeditions

Euro-American (EA) beaver trapping was temporally and spatially concentrated. It began in the 1600s on the East Coast and along the Mississippi and Missouri Rivers, in the early 1700s on the West Coast, and into the Interior United States in the late 1700s and early 1800s (Phillips 1961). The arrival of trappers in an area predated most settlement and scientific and military surveys by at least several decades, with a few exceptions. One exception is the East Coast where settlement and trapping co-existed in time (Cronon 1983) and numerous writings exist from the 1600s and 1700s on the local natural history of those areas (Meisel 1924). Other exceptions are the Lewis and Clark (1804 to 1806), Long (1819 to 1820), and Pike (1805 to 1807) expeditions in the West (Phillips 1961). These written observations, combined with later trappers' journals and records from fur companies, reveal complex, multi-channeled rivers abundant with beavers and beaver dams.

Yet, it was not these early records but those of the later GLO surveys and scientific and military expeditions that have been used to reconstruct the geomorphic and ecological characteristics of watersheds prior to settlement. Embedded in this reliance on the GLO notes for pre-settlement conditions has been an unspoken assumption that "the public land surveys were carried forward in virgin territory—unexplored and unmapped—in advance of settlement" (Clements 1985). However, regardless of the area examined, changes to the drainage network were well underway by the time the GLO surveys and various expeditions arrived, with the degree of change observed influenced by the number and type of EA disturbances that had occurred post-trapping.

The GLO surveys began in 1785 with the passage of the Land Ordinance. The first survey took place in Ohio in 1785 with subsequent surveys proceeding westward in response to pending EA settlement (Clements 1985; White 1996). It was a formalized gathering and storing of information. However, even by 1785 the area east of the Missouri and lower Mississippi Rivers had already been heavily trapped (Phillips 1961). In the New England landscape, beavers had ceased to be a dominant feature as early as the late 1600s (Cronon 1983). By the late 1700s to early to mid-1800s the beaver dams had been replaced by thousands of water-powered mill dams in New England and the Mid-Atlantic States. The mill dams trapped sediments eroding off the valley and hillslope in response to agriculture and logging, burying the beaver-created wetlands (Walter and Merritts 2008). In the Southwest and Intermountain West, trapping and the GLO surveys were more coincident in time but still separated by a decade or more (table 5). Some early researchers in the West acknowledge the occurrence of beaver trapping in their study areas and its implications (Dobyns 1981; Gregory 1917; Gregory and Moore 1931; Hendrickson and Minckley 1984; Leopold 1951), but the loss of beavers as a regional disturbance with major geomorphic and hydrologic significance was missed.

The temporal differences between when trapping occurred versus the GLO surveys and early expeditions was compounded by differences in their spatial geographies. Trappers followed streams in their search for beavers. In contrast, the GLO surveys recorded information about the land and its resources along linear grid lines spaced

Table 5—Estimated timing of beaver trapping, observations of discontinuous arroyos and incised tributaries, and baseline GLO survey (Source: Fouty 2003.)

Site: San Pedro River, AZ

Dates trapped: 1826-1827 (Pattie 1831)

Pattie and his party trap the river in March 1826 and take 200 beavers. They trap the river again in October 1827. No numbers given for the second time.

Next observation: Military expeditions: 1846, 1852, 1859 (Leopold 1951).

1846 – Description of vegetation patterns in area (Johnston 1847).

1852 near Pomerene: The stream banks not less than 8 to 10 feet high (Bartlett 1854).

1859 – There is a discontinuous gully near Pomerene. The river has a "width of about twelve feet and a depth of twelve inches [water depth], flowing between clay banks ten or twelve feet deep, but below it widens out and from beaver dams and other obstructions overflows a large extent of bottom land, forming marshes densely timbered with cottonwood and ash Hutton (1859)."

Estimated time between trapping and next observation: 19 to 20 years.

Baseline GLO surveys: 1851, 1865, 1867 (White 1996).

Site: Diablo Range, CA about 10.6 to 15.5 miles west of the San Joaquin River (Bull 1964)

Dates trapped: 1829 to 1843 (Phillips 1961).

Hudson's Bay Company trapped in California beginning in 1829 until 1843, returning "every year to trap the Sacramento-San Joaquin River systems and the area around the San Francisco Bay (p. 544)." The company took from the Bay area alone 10,860 beaver between 1830 and 1839.

Next observation: GLO surveys in early 1850s (Bull 1964).

GLO surveyors noted the existence of "traces of older gullies on some of [alluvial] fans indicate that entrenched channels existed before sheep were brought into California in 1853 and before large-scale cattle ranching was introduced in western Fresno County."

Estimated time between trapping and next observation: 9 to 25 years

Baseline GLO surveys: 1852 to 1854 (Cooke and Reeves 1976).

Site: Rio Puerco, NM, a tributary to the Rio Grande (Bryan 1928a)

Dates trapped: 1823 to about 1838 (Weber 1971).

"In 1823, however the fur trade from New Mexico had scarcely begun….most trappers certainly centered their operations on the virgin streams of the Pecos and Rio Grande valleys. The beaver supply in this convenient area was already being depleted" and by 1824 trappers were heading west. In 1827 American fur trappers were floating down the Rio Grande trapping as they went. 1832 to 1838 trapping occurs around the settlements along the Rio Grande valley.

Next observation: Military expedition 1846 to 1847, 1849 (Bryan 1928a).

Abert (1847): banks were 10 or 12 feet high and vertical at a point west of Albuquerque. Banks were 30 feet further upstream near a ruined town. Simpson (1849): channel was 100 feet wide, contained stagnant pools of water; banks were 20 to 30 feet high about 5 miles above Cabezon (small village on the river). Late 1880s: many settlers testify that in many places the river had no banks or only small ones and in flood the river spread out over the entire valley floor.

Estimated time between trapping and next observation: 9 to 23 years

Baseline GLO surveys: 1855 (Bryan 1928a).

Site: Non-specified tributaries in the Colorado River region (Dellenbaugh (1912)

Dates trapped: 1824 to probably late 1830s (Chittenden 1954; Phillips 1961).

All the major tributaries of the Colorado River were trapped.

Next observation: The Powell expedition of 1871 or 1872 (Gregory and Moore 1931).

"I noted the same characteristics [trenching of stream beds] (and others probably also noted) years ago in places where there were no cattle and never had been"….. "I have seen earth-cliffs 30 to 40 feet high with all the characteristics of a rock-cliff erosion" (Dellenbaugh 1912).

Estimated time between trapping and next observation: 33 to 47 years.

Baseline GLO surveys: New Mexico: 1869; Arizona: post-1867; Utah: post 1855; Colorado: post 1880 (White 1996).

1 mile apart. The GLO surveys focused first on those areas that were about to be settled or were in the process of being settled by Euro-Americans, leaving large portions of each State unsurveyed until later (Clements 1985; White 1996).

An example is the early military expeditions into Arizona and New Mexico. They entered the Gila River drainage from southern New Mexico via the Lordsburg Plain (Leopold 1951) making their observations of pre-settlement channel incision restricted to the middle and lower Gila River Basin (e.g., San Pedro River, the Santa Cruz River). The upper tributaries (e.g., San Francisco River, East and West Forks of the Gila River) were bypassed and changes unrecorded. Yet references to discontinuous arroyos ending at wetlands on the San Pedro River in 1846 (Cooke and Reeves 1976; Hastings and Turner 1965) suggest that these features would have existed in the upper watershed as well because the entire basin had been trapped between 1826 and 1834 (Pattie 1831; Weber 1971).

I am familiar with the upper Gila watershed, having collected stream data on several of its tributaries in the 1990s. These tributaries contain the appropriate valley characteristics for beaver dam complexes and beavers and I observed beaver sign on the East Fork of the Gila in 1993, 1994, and 1995. Therefore, had the GLO surveyors and early military and scientific expeditions explored the upper watershed, they likely would have observed areas where abundant beaver dam complexes and their relationship to wet meadows persisted. These observations would have led future researchers to ask different questions and come to different conclusions about the causal mechanisms leading to arroyo development.

The limited and selective exploration of the Southwest prior to EA settlement is an example of what Graf (1984) referred to as a "spatial bias." He saw this bias as "a major hazard in geomorphic theory development because of the relatively small size of the geomorphic research community." The limited number of researchers means that "individual scientists can affect the development of theory with relatively few publications, and therefore *the field origins* [emphasis added] of those few publications [or observations] assume disproportionate importance" (Graf 1984). This is what happened in the case of the spatially limited but high quality GLO surveys and early expedition records in these areas post-trapping. The fragmented but still visible influence of a once-abundant beaver population and the impact of recent trapping on drainage stability appeared localized. Thus their significance at a regional scale was missed by later researchers who would utilize these records.

Arroyo Formation in the Southwest and Intermountain West

The Role of Beaver Trapping

The presence of pre-historic arroyos and pre-EA settlement arroyos in the Southwest and Intermountain West (Balling and Wells 1990; Love 1979) has been central to the question about whether EA livestock grazing, climate change, random-frequency events, or some combination was the dominant causal mechanism that led to widespread arroyo development after EA settlement (Cooke and Reeves 1976). Their presence led some early researchers to suggest that climate was the dominant causal mechanism and EA livestock grazing merely a "trigger pull which timed a change about to take place" (Bryan 1928a). This perspective suggested that streams in these regions were inherently sensitive to climatic variability.

The GLO surveys and early expeditions recorded two categories of features: one indicative of a stable fluvial system (wetlands, wet meadows), the other indicative of a destabilized fluvial system (discontinuous arroyos, actively incising tributaries), often within the same drainage (Cooke and Reeves 1976; Hastings and Turner 1965; Hendrickson and Minckley 1984). The active nature of the channel incision suggested that the destabilization had been fairly recent. Determining whether a long-term beaver presence followed by trapping could explain this mix of observations, a direct relationship between EA trapping and arroyo formation was considered supported if (1) trapping occurred in the area, (2) the time interval between trapping and the next observation (i.e., 15 years) was longer than the time needed for substantial channel incision to occur (i.e., <10 years), and (3) the magnitude of the observed channelization could have occurred within the intervening time (Fouty 2003). In this case, beaver dam failures and non-repair would explain the channelization observed. When the interval between trapping and the next observation was shorter than 10 years, this suggested that large precipitation events and localized dam failures may have interacted synergistically to enhance large floods, thereby accelerating the rate of dam failures and channel incision. A literature review found that the features observed by the surveys and expeditions in the Southwest and Intermountain West occurred either in areas directly mentioned as being trapped or in the general area. The temporal separation between trapping and the next observations of stream conditions and site characteristics was 9 to 47 years (table 5).

The widespread and rapid removal of beavers throughout these areas led to the development of multiple base-level drops within individual drainages as dams failed and were not repaired. The impact of multiple base-level drops on channel development and drainage network expansion would have been amplified by the period of above-average precipitation from 1835 to 1849 observed in the tree-ring data (D'Arrigo and Jacoby 1991; Meko 1990; Meko et al. 1991). This period occurs shortly after trapping ceased in these areas but before the GLO surveys and early expeditions arrived. A second period of above-average winter precipitation, also identified in the tree-ring data, occurred from 1905 to 1920, or 1928 depending on the tree-ring chronology (D'Arrigo and Jacoby 1991; Meko 1990). This second wet period post-dated not only beaver trapping but settlement, widespread livestock grazing, and other land use activities. It is this second period of above-average precipitation that contributed to the large floods that widened and incised many streams in the West (Burkham 1972; Cooke and Reeves 1976), leading to a further expansion of the channelized network.

The early researchers who sought a causal mechanism to explain the pre- and post-settlement arroyos and changes in watershed hydrology did not understand the significance of the remnant populations of beaver and their scattered dams. Nor were they aware of the period of above-average precipitation that had occurred from 1835 to 1849. When impacts of the two events are combined, a different, more complex causal mechanism for the observations recorded by the GLO surveys and early expeditions and the later increase in flood frequencies and magnitudes appears. The causal mechanisms expand to include a long-term beaver presence followed by beaver trapping followed by above-average precipitation. These series of events explain not only the discontinuous arroyos and actively incising tributaries, but the occurrence of drainages in which the arroyos terminated at the base of a wetland.

A long-term beaver presence as an explanation for the wetlands (or cienégas) found in the Southwest is supported by Hendrickson and Minckley (1984). They found that mid-elevation wetlands characterized by permanently saturated, highly organic reducing soils occurred where (1) groundwater intersected the surface, (2) discharges were stable, and (3) flood peaks were low, minimizing the potential for scouring flows and channel incision. The features they identified causing groundwater to intersect the surface included upfaulted bedrock, changes in base level of the receiving stream, stream impoundments by landslides, and the development of a convex-concave profile. In their discussion of the convex-concave profile, they identified two mechanisms leading to its development: the deposition of coarse sediments and the placement of beaver dams along the stream. However, the influence of beaver dams extends beyond the profile. Similar to landslides, though on a smaller scale, beaver dams impound streams, provide local base-level control, and raise the base level of the channel by reducing ACC as they pond water and trap sediment. Though not as stable as bedrock, as long as beavers are present in the system to repair the dams, the dams will operate as a "continuously renewed, erosionally resistant substrate" (Parker et al. 1985).

The long-term presence of beaver dam complexes also creates stable wetlands. These wetlands are highly resistant to climatic variability and disturbance (Ives 1942; Naiman et al. 1986, 1988), and can have long residence times on the landscape when undisturbed (Hendrickson and Minckley 1984; Ives 1942; Naiman et al. 1988; Warren 1926). The dam complexes provide the two other requirements identified by Hendrickson and Minckley for wetland development (low flood peaks and stable discharge). Large ponds and wetlands in headwater streams have been observed to effectively dampen the effects of both large runoff events and prolonged drought (Grasse and Putman 1956; Hillman 1998; Hood and Bayley 2008). Beaver dams decrease flood peaks by storing water in the ponds and reducing ACC such that during high-flow events there is rapid access to the valley floor where potential flood storage and roughness are greater. In turn, the increased frequency of valley-floor flooding leads to higher water tables that stabilize base flows, minimizing the impacts of drought.

Once trapping occurred, the dams were no longer maintained and they ceased to act as "continuously renewed, erosionally resistant substrate" akin to bedrock. Instead they became points of base-level drop and knickpoint initiation. However, the greater resistance of wetlands to incision, compared to the dam sediments, would have effectively halted the headward migration of a knickpoint generated by a base-level drop downstream. The result was the development of the observed discontinuous channels interspersed with wetlands. It is possible that these drainages may have remained a mix of channels, ponds and wetlands without further EA disturbances. The wetlands and lush grasses and willows along channels would have maintained channel and stream bank stability and thus kept channels narrow, the stream-valley floor hydrologic connection high, and downstream flood peaks dampened.

Other areas within the West showed patterns and sequencing of change similar to that found in the Southwest. An example is the work done by Buckley (1992) on Camp Creek, a tributary to the Crooked River, and located in central Oregon. He found that the area had been trapped between 1824 and 1830 by Peter Skeen Ogden and his party and his journals reference plentiful beavers, willows, and aspen (Buckley 1992). Later records from military expeditions between 1858 and 1864 note lush grasses, willows, swampy areas, and abundant beavers and beaver dams along Camp Creek. By 1876, references to beavers are absent in the GLO notes, though they still mentioned the presence of large swampy areas along Camp Creek and narrow channel widths (10 to 33 ft). However, the GLO notes also mention that several homesteaders had been living along Camp Creek and its tributaries since 1871, which may account for the lack of beavers. Livestock were in the area by 1876 with numbers increasing into the early 1900s. By 1905 Camp Creek had incised 25 ft and widths had increased to 60 to 100 ft wide (Buckley 1992).

Not all areas had wetlands mixed with arroyos and incising tributaries. Places where the GLO notes or early expeditions mention arroyos but not wetlands include the Colorado Plateau (Dellenbaugh 1912), the Zuni River in Arizona (Balling and Wells 1990), the Rio Puerco in New Mexico (Bryan 1928a), and the Diablo Mountains in California (Bull 1964). F.S. Dellenbaugh, a topographer on the Powell expedition of the Colorado River area in the 1870s (Gregory and Moore 1931), mentioned seeing earth-cliffs bordering unnamed tributaries in this area in the 1870s that were 30 to 40 ft high. He observed these in areas where EA livestock grazing had not yet reached. He suggested that the tributaries were responding to a drop in base level on the main stem that had occurred for some unknown reason (Dellenbaugh 1912). The Colorado Plateau had been trapped in the 1820s and perhaps as late as the 1840s (Phillips 1961). Dellenbaugh's observations in the 1870s (30 years later) would be consistent with beaver-dam failures on tributary streams triggering multiple points of base-level lowering. It is possible that wetlands were present, but not observed. It is also possible that topography, the presence of Native Peoples and their villages, or both, eliminated wetlands prior to the next EA observation.

The Role of Native Peoples

The influence of Native Peoples on arroyo development and the presence or absence of wetlands cannot be ignored. The difference between the impacts of beavers and beaver trapping versus Native Peoples' efforts may simply be one of aerial extent. Native Peoples would have influenced the areas around their villages creating localized changes (Dobyns 1981) while beavers would have had a wider distribution. Reagan (1924) observed that "every side-wash, canyon and flat had its village or villages, its dams, ditches and reservoirs, as is readily seen by examining the region." He argued that irrigation systems and check dams built by Native Peoples were responsible for the development of ponds, wetlands, and aggrading surfaces. Reagan's (1924) descriptions of height, composition and locations of the check dams are similar to beaver dams. The check dams were composed of earth, about 5 ft tall and, like beaver dams, would have required constant maintenance. Dobyns (1981) also supported the hypothesis that Native Peoples played a large role in reducing erosion via their check dams. He felt that their reduction in numbers due to contact with EA diseases and conflicts would have led to decreased dam maintenance and renewed erosion as the dams failed. The changes in the drainage network and hydrology would have been similar to those that occurred due to widespread beaver dam failures. Some of the dams attributed to Native Peoples may thus have been beaver dams given their wide distribution prior to EA trapping.

The Zuni River, located in Arizona and a tributary to the Little Colorado River, provides possible insight into this question of Native Peoples' influence because documentation exists of arroyos that pre-date both Spanish and EA activity. These early arroyos date from about 1680. Tree-ring dates indicate that the Zuni River had eroded to its present level by 1776 when Fray Dominguez observed an arroyo adjacent to the Zuni Pueblo as well as arroyos upstream of the pueblo (Balling and Wells 1990). Balling and Wells (1990) used modern precipitation records (1897 to 1985) and post-settlement arroyo development to analyze potential causes of early arroyo formation. They suggested links between arroyo formation and changes in local precipitation patterns, particularly precipitation intensities. However, these very early arroyos were in the vicinity of a pueblo, complicating the direct link to precipitation. The Native Peoples may have deliberately or unintentionally altered some feature of the landscape that caused arroyos to form, such as the digging of an irrigation trench, failure of a check dam, or removing beavers from an area. Grazing by Native Peoples' sheep and horses, which had arrived with the Spanish (Love 1916), may have also contributed to arroyo formation by reducing upland vegetation around the pueblo. References from the 1847, 1849, and 1852 expeditions into this area and elsewhere in eastern Arizona mention the presence of numerous Indian horses and sheep and areas with limited forage for their mules (Leopold 1951). The link between arroyo expansion in the Zuni River area and EA beaver trapping after 1849 is clearer because the timing of trapping in the area and the period of above-average precipitation (1835 to 1849) are known.

The Little Colorado River Basin where the Zuni River occurs was trapped for beavers in the 1820s and 1830s (Gregory and Moore 1931; Phillips 1961). Leopold (1951) cites references to the presence of beaver lodges in 1852 on the Little Colorado River slightly upstream from the town of Holbrook. This would place the lodges roughly 36 linear miles downstream of the confluence of the Zuni River and the Little Colorado River. In addition, the 1852 expedition observed in one place on the Zuni River below the village of Zuni (now a dry wash) "a few populars… and near these trees was a beaver-dam" (Leopold 1951). While the observation of populars [poplars] and beaver dams in this area may have been a rare sight in 1852, it indicates that beaver were present in the area. Their loss would have made streams more susceptible to channelization during the wet period that followed their removal especially in those areas where vegetation had been altered by Native Peoples' livestock or agriculture. Beaver dam failures likely combined with human check dam failures, their similar appearance and function triggering similar effects. The lack of references to wetlands in the area around the Zuni Pueblo by the early military expeditions suggests that the long-term presence of Native People may have already modified conditions such that wetlands had been lost in response to earlier activities.

Reexamining Changes on the Gila River in Light of Beaver Trapping

This analysis of changes on the Gila River builds on an earlier study by Burkham (1972) in which he assessed the likely causes of the channel widening between 1905 and 1917 on the Gila where it flowed through the Safford Valley of Arizona. This river basin, in southwestern New Mexico and southeastern Arizona, is a watershed scale example of how interpretations of causal mechanisms of change can vary once placed in a historical context that includes beaver trapping and more climate information.

The drainage area contributing to the Gila where it flows through the Safford Valley is about 7,900 miles^2. In 1875, the average channel width was less than 150 ft. Between 1905 and 1917 the average width increased to about 2,000 ft during several large magnitude winter floods (Burkham 1972). The bulk of the widening occurred in 1905 and 1906 and the source of the large floods was the mountainous headwaters of the Gila River. Examination of stream discharge and precipitation data available after 1910 shows a strong correlation between large magnitude floods in the Gila River and rain-on-snow events or high-intensity, long-duration storm events (Burkham 1970). Based on this correlation, Burkham (1972) concluded that the large flood magnitudes in 1905 and 1906 were the result of precipitation events in the headwaters. His conclusions relied on the tree-ring data of Stockton and Fritts (1968) for Arizona, which identified 1907−1926 as the wettest 20-year period since 1650.

Burkham (1972) also considered whether livestock grazing, rather than precipitation, could have been responsible for the large magnitude floods that occurred between 1905 and 1917. He concluded that livestock grazing was not a factor based on his understanding that livestock appeared to be largely restricted to the lower watershed while the floodwaters had their source in the upper watershed. However, livestock grazing had occurred in the upper watershed. Swift (1926) noted livestock grazing on Bonita Creek, a tributary to the Gila River upstream of the Safford Valley, as early as 1884. Winn (1926) noted livestock grazing on the West Fork of the Gila River in the 1880s. A 1993 environmental impact statement for a cattle allotment on the East Fork of the Gila River stated that the area was severely overgrazed by 1908 (USDA Forest Service 1993). The reference to overgrazing indicates that livestock were using the East Fork drainage prior to 1908. There is no reason to assume that the West Fork of the Gila and Bonita Creek would have been grazed in the 1880s while the East Fork of the Gila, San Francisco River, and other tributaries would have been ignored by early livestock owners.

In this arid landscape, the impact of livestock in the tributaries would have been high around the streams. Hendrickson and Minckley (1984) concluded that grazing in the 1880s would have been concentrated within a 3-mile radius of streams because livestock rarely travel more than 3 miles from a water source and only lightly graze areas greater than 1.8 miles from water. The result would be concentrated use along the tributary stream corridors accelerating the rate at which riparian vegetation and bank resistance to erosion decreased. Livestock grazing in the upper watershed would have also decreased upland vegetation, decreasing surface roughness. The reduced roughness and resistance to erosion would have resulted in gully development in the uplands, thus facilitating the increase in storm runoff reaching the stream channels. The changes that occurred in Mountain Meadows, Utah, in 1884 is an example of this gully development and captures the speed at which it could occur (Cottam and Stewart 1940, table 3).

Increases in runoff leading to elevated streamflows would have enhanced and accelerated changes triggered by the earlier beaver trapping. The Verde, Salt, San Pedro, San Francisco Rivers (tributaries to the Gila), as well as the Gila itself are all mentioned by name as being trapped between 1826 and 1834 (Pattie 1831; Weber 1971). While not specifically mentioned, the smaller tributaries would have also been trapped as trappers systematically moved through the area. Thus, EA livestock grazing in the Gila River basin becomes the second, not first, large-scale regional disturbance in the area.

While Burkham (1972) focused on the 20-year period from 1907 to 1926 identified in Stockton and Fritts (1968), they also examined 10-year intervals. In this interval set, 1831 to 1840 showed up as having a relatively high probability of above normal precipitation. This time interval is close to the 1835−1849 interval identified by later researchers (D'Arrigo and Jacoby 1991; Meko 1990; Meko et al. 1991), both intervals post-dating intensive trapping. Thus, effects of beaver trapping (1826−1834), followed by a wet period (1831−1840 or 1835−1849), and then by intensive grazing in the upper watershed (early 1880s) would have interacted synergistically to accelerate drainage network development in the headwaters. The result would be more rapid transfer of water from the upper to the lower watershed, increasing flood frequencies, and amplifying flood magnitudes for precipitation events of all sizes.

The above scenario of a watershed that had recently undergone changes of such a nature that it was now responding to precipitation events differently is supported by the oral history of the Gila River Pima Indians and historical newspaper accounts that predate the 1910 installation of stream gages in the watershed. Floods occurred in 1833, 1869, 1880, 1884, 1889, 1891, 1895, and 1896 (Dobyns 1981; Burkham 1970). The floods of 1833, 1895, and 1896 are of particular interest. The 1833 flood was the first major downstream flood recorded in Gila River Pima Indian oral history (Dobyns 1981). Since trapping had been ongoing in the upper watershed since 1826 and mostly done by 1831 (Pattie 1831), Dobyns (1981) suggests that this flood may have been the result of the abrupt collapse of beaver dams destroyed in the preceding decade. This scenario is reasonable given that large discharges have been documented occurring in response to abrupt dam failures (Butler 1989; Hillman 1998) and the tree-ring data that recorded a period of above-average precipitation around that time (1830−1841 or 1835−1849). The floods of 1895 and 1896 were unusual because they occurred during the Southwest's third most severe drought in the last 1,000 years (D'Arrigo and Jacoby 1990). These floods are a strong indication that the drainages in the upper watershed had changed.

The timing of the GLO surveys and early expeditions and their spatial geographies influenced the direction that future researchers went as they sought to explain arroyo formation and large magnitude flood events post-EA settlement. When the surveys and expeditions arrived in the Southwest in the 1850s, beavers had somewhat recovered from near extinction. There would have been little awareness of how much their numbers have been reduced or of the precipitation events that followed. Beavers were observed on the San Carlos River in 1846 (Leopold 1951), on the Little Colorado River in 1884 (Colton 1937), and on the San Pedro River in 1858 and as late as 1882 (Hastings and Turner 1965).

The 1858 observation on the San Pedro River is of interest because it notes the following spacing of beaver dams:

> The San pedro river as they Call it—is a stream one foot deep six ft wide and runs a mile and half an hour and in ten minutes fishing we Could Catch as many fish as we Could use and about every 5 miles is a beaver dam this is a great Country for them (Hastings and Turner 1965).

Comparing the 1858 dam spacing to the numbers of beavers taken by trappers in 1826 from the San Pedro and to dam spacing found today in basins with relatively unexploited beaver populations makes clear the magnitude of change that had occurred. In 1826, trappers took 200 beavers from the San Pedro River and found beavers so abundant that they named it the Beaver River (Pattie 1831). Examples of average dam frequencies include 17 dams/mile in two drainage basins in Quebec (Naiman et al. 1986), 4 dams/mile in the Kabetogama Peninsula in Northern Minnesota (Naiman et al. 1988), and up to 6.5 dams/mile in Bridge Creek in eastern Oregon (Demmer and Beschta 2008)—all much greater than the 5 mile per dam spacing noted on the San Pedro River in 1858.

Explaining the Absence of Arroyo Formation From 1750 to 1825 Despite Large Herds of Spanish and Mexican Livestock

The relative contributions of livestock grazing versus climate as the cause of widespread arroyo formation in the Southwest post-EA settlement has been in question for nearly a century. Part of the reason for the uncertainty is that large livestock herds existed twice in the Southwest (1750−1825 and 1870−1905) but widespread arroyo formation occurred only once, from 1870 to 1905 (Cooke and Reeves 1976; Denevan 1967). Both periods of large herds had below-normal seasonal precipitation. Possible explanations for this discrepancy in landscape response to livestock grazing have included: (1) a gradual, long period of change in climate that altered vegetation to the point that watersheds in the late 1800s were more sensitive to livestock grazing than in the late 1700s to early 1800s; (2) the combination of overstocking the range and severe summer drought that occurred in the late 1800s but not in the prior period; and (3) some combination of the two (Cooke and Reeves 1976; Denevan 1967). Another explanation involves the change in beaver numbers and distributions between the two periods of intensive grazing.

Beavers were abundant in the late 1700s and early 1800s but greatly reduced by the late 1800s due to EA trapping in the 1820s and 1830s. Therefore, Spanish and Mexican herds would have grazed on landscapes that pre-date EA beaver trapping while the EA livestock herds grazed on landscapes that post-date trapping. The presence of abundant beavers during the time of Spanish and Mexican livestock grazing would have minimized any impacts that reduced upland vegetation had on runoff and potential flood magnitudes. Beaver-created wetlands and ponds would have provided stability to the fluvial systems during periods of drought and heavy rainfall (Bailey 1936; Grasse and Putman 1950; Hendrickson and Minckley 1984; Hillman 1998; Hood and Bayley 2008; Johnston and Naiman 1990). Despite the heavy sheep and cattle grazing, the dams would have kept ACC low, causing the additional water to be distributed onto the valley floor where its erosive power was less. When dam failures did occur, they would have been repaired or only localized, preventing the development of permanent arroyos or a channelized drainage network. In addition, use of the upper watershed for livestock grazing was likely much more limited during the earlier period than after the EA heads arrived (Love 1916).

When the large EA livestock herds arrived in the 1870s and began moving into the headwaters (Love 1916), the buffering effect of beavers and intact beaver dams had been gone for 30 to 40 years. The period of above-average precipitation, post-trapping but prior to EA settlement and grazing, would have accelerated dam failures and channel development. While agriculture increased in the lower watershed and other activities such as road building and logging contributed to changes on the land, it would be livestock grazing in the upper watershed that made the next large contribution to channel changes because it was the most widely dispersed and use would have been concentrated along the stream corridors. Thus the extensive arroyo development from 1870 to 1905 was the response of an increasingly destabilized system in which one regional EA disturbance (trapping) was overlain by another regional disturbance (grazing), along with other localized EA impacts. As a result, even small climate events were now capable of increasing the channel network (table 3) and flood magnitudes as demonstrated by the frequent pre-1900 floods despite periods of drought.

The Question of Stream Sensitivity to Climate Variability

Adding beaver trapping into the story with the addition of newer tree-ring data helps answer the question: Are Southwestern streams and riparian zones inherently sensitive to climatic variability? The answer to the question is "no," as long as stabilizing influences, such as abundant beavers and well-vegetated landscapes, are maintained because climatic variability is the norm. Using tree-ring data from northern New Mexico, D'Arrigo and Jacoby (1991) identified five periods of substantial drought and five periods of above-average winter precipitation over the last 1,000 years. Therefore, neither the drought nor the above-average precipitation in the late 1800s and early 1900s is unique, though the abruptness of the shift from severe sustained drought to above-average precipitation in the early 1900s does not appear to have a match in the tree-ring data (D'Arrigo and Jacoby 1991). Regardless, abundant research supports the ability of beaver ponds and wetlands to mitigate the effects of both drought and abundant precipitation on streamflow and stream systems (Bailey 1936; Beedle 1991; Grasse and Putman 1950; Hey and Philippi 1995; Hillman 1998; Hood and Bayley 2008; Schaffer 1940). Thus, rather than instability and sensitivity to climatic variability being an inherent characteristic of streams in the Southwest and elsewhere, this responsiveness is the result of EA beaver trapping with impacts compounded as subsequent EA disturbances occurred.

From Past to Present: Placing Hydraulic Geometry Relationships in Their Historic Disturbance Context

The early GLO surveys and expeditions lacked information on numbers and distributions of beavers and the appearance of stream ecosystems pre-trapping. The speed of the changes, the timing, and the spatial geographies of the surveys and early expeditions versus trapping, and the continued presence and perceived abundance of beaver post-EA trapping, gave the impression that the significance of beaver trapping at the watershed and regional scale was minimal. It was into this post-trapping, changing landscape that the field of geomorphology emerged in the 1870s. However, it was not until the 1940s that fieldwork and quantification of field data took hold in the discipline (Morisawa 1985). By then most streams in the lower 48 States had undergone multiple adjustments in channel morphology and hydrology in response to various land uses and climatic events. Evidence of beavers as a defining influence on stream ecosystems had become lost by the late 1700s to early 1800s in the East as other land uses buried beaver-created wetlands beneath feet of sediment (Walter and Merritts 2008). It had become fragmented by the 1850s in the

Southwest and Intermountain West by the time the GLO surveys and expeditions arrived, and invisible everywhere by the 1940s.

Using the limited tools and information at their disposal, the early geomorphologists developed relationships that continue to define the discipline and influence stream restoration efforts. However, new information and the development of new tools require that the relationships and observations found in early publications—publications covering such topics as hydraulic geometry (Leopold and Maddock 1953), formation of river floodplains (Wolman and Leopold 1957), and channel patterns (Leopold and Wolman 1957)—be reevaluated as to their meaning and appropriateness as guiding principles in stream restoration. Leopold and Maddock's (1953) hydraulic geometry relationships serve as an example of how the interpretation of data and observations change once new information is incorporated into the analysis.

Leopold and Maddock used data from 112 stream gages to develop their hydraulic geometry relationships. They chose data from a diversity of geographic locations (fig. 21a), physiographic and geologic types, and sizes because their intent was to examine channel morphology, stream velocity, suspended sediment loads, and discharge information for general trends. The author found gage installation dates for 104 of their 112 gages (http://water.usgs.gov). Ninety-four percent of these gages were installed after 1900 (fig. 21b) and after two waves of regional, large magnitude EA disturbances (table 6). When their data are placed within this historic disturbance context, it becomes clear that the hydraulic geometry relationships they developed, and the processes and rates of change they observed, reflected highly altered fluvial systems. By the time the gages were installed, the drainages had become interconnected systems of channels, the streams had become entrenched, over-wide, and hydrologically disconnected from their valley floors, and beavers no longer played their once defining role.

The first regional disturbance that influenced all their stream gages was beaver trapping. The second regional disturbance varied depending on location. For the stream gages east of the Mississippi River, the next regional disturbance was the building of thousands of water-powered mill dams. These dams trapped the sediment eroding off hillslopes and valley bottoms due to logging and agriculture. As time went on, the mill dams failed and new channels developed (Walter and Merritts 2008). For the lower Midwest stream gages (Kansas, Nebraska, and Missouri), the next regional disturbance was intensive agriculture in which abundant wetlands and beaver ponds were drained (Hey and Philippi 1995). The magnitude of stream changes in this area was captured by Schumm and Lichty (1963) in their work on the Cimarron River in southern Kansas. The Cimarron River increased in average width from 50 to 1,200 ft between 1874 and 1939 over roughly 175 miles with the variability in magnitude reflecting differences in bank composition and cohesiveness once the stabilizing vegetation had been removed (fig. 22).

Finally, for the Northern Rockies/Rockies stream gages (Montana, North Dakota, South Dakota, and Wyoming), it is livestock grazing that is the next regional disturbance. Leopold and Miller (1954), in their work on alluvial valleys in Wyoming, discuss the amount of channel incision that had occurred in this area. They specifically reference some of the same streams used by Leopold and Maddock (1953) in their hydraulic geometry paper. Thus by the time their stream gages were installed, the drainages conveyed water and sediment very differently than they once had.

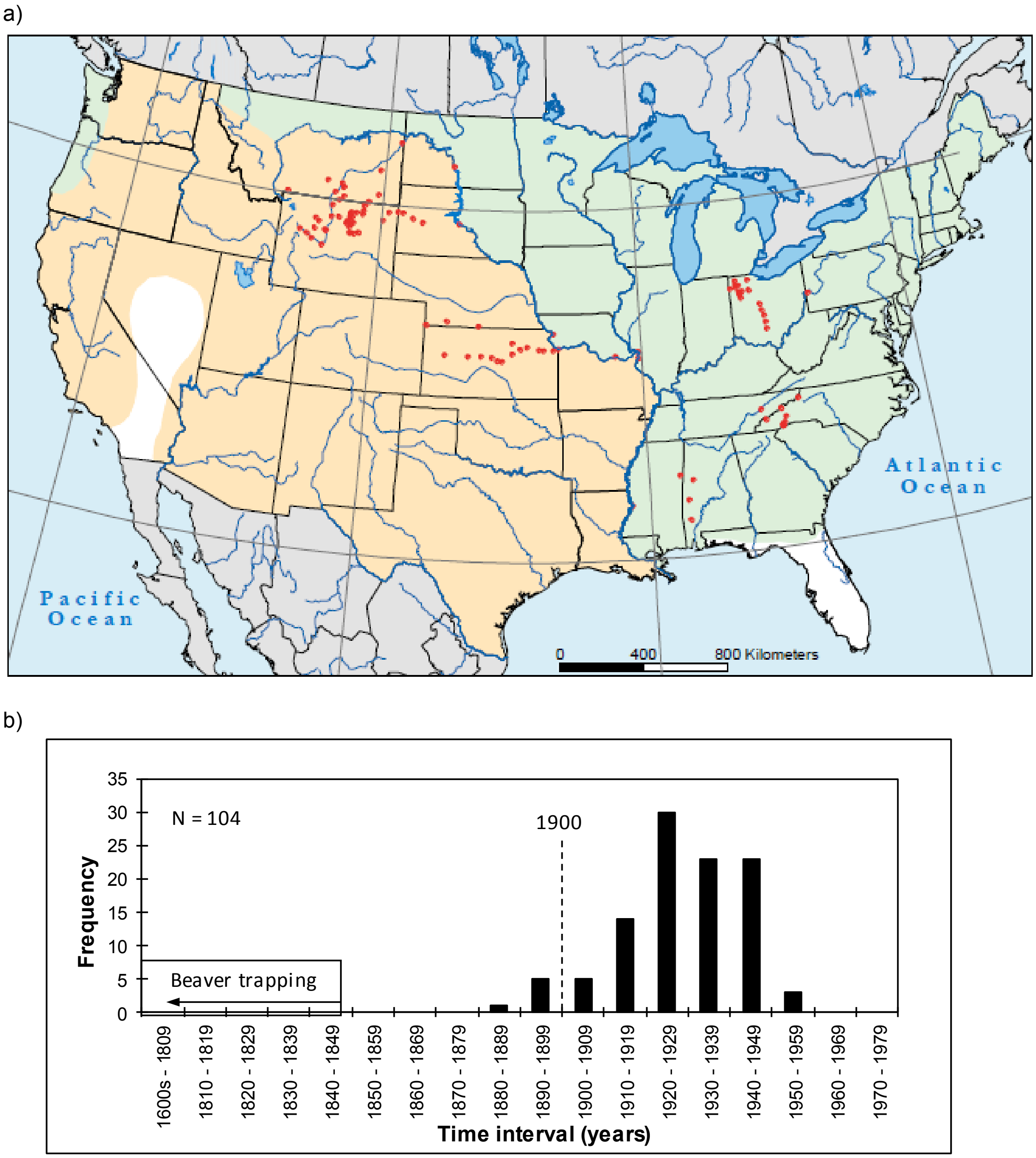

Figure 21—Spatial and temporal distribution of the stream gages used by Leopold and Maddock (1953) and the generalized timing of beaver trapping in the lower 48 States (source: Fouty 2003). **(a)** Spatial distribution of the stream gages. Gages are represented by the RED dots (N = 104), GREEN = beaver trapping from 1600s to 1785, ORANGE = beaver trapping from 1810 to 1850, WHITE = no known beaver trapping. **(b)** Installation dates for stream gages (sources: Installation dates U.S. Geological Survey website http://water.usgs.gov. Eight of the gages listed in Leopold and Maddock 1953 were not listed on the website; beaver trapping dates Phillips 1961).

Leopold and Maddock's hydraulic geometry relationships have become one of the guiding principles of fluvial geomorphology. While their relationships have been refined and made more place-specific since 1953, the conceptual model of drainages being interconnected channels remains. The continued use of these and other relationships developed from highly altered stream systems means that restoration efforts end up reinforcing the damage and loss of system resiliency that began with the fur trade in the 1600s.

Table 6—Relative temporal relationships of Euro-American disturbances and their impact on watershed hydrology and geomorphology (source: Fouty 2003.)

Beaver establish a long-term presence

Upper watershed: Drainage network pattern a mix of ponds, wetlands and channels. Complex mosaic of riparian vegetation. Stream-valley floor hydrologic connection high and the valley floors frequently flooded. Stream ecosystem has low sensitivity to climatic variability, high resistance to disturbance and recovers rapidly after a disturbance.

Lower watershed: Flood magnitudes and the frequency of large magnitude floods decreases and flood durations increase.

First large-scale Euro-American disturbance: Beaver trapping

Widespread, temporally concentrated, and systematic removal of beaver from watersheds.

Drainage network transition I

Upper watershed: Dams fail, ponds drain and stream incises into fine sediments trapped behind the dams. Drainage network shifts to an increasingly channel-dominated network. Stream-valley floor hydrologic connection decreases as channels incise and widen. Wetland and riparian vegetation patterns begin to change in location and abundance in response to localized channelization, dropping water table, decreased valley floor flooding and beaver forage, and exposure of pond sediments. Reaches with intact wetlands continue to have low sensitivity to climatic variability but other areas have increased sensitivity due to channelization. Decreasing resistance to climatic variability and disturbance. Increased channelization in the upper watershed results in more rapid transfer of water from the upper to lower watershed. Drainage network a mix of channelized and nonchannelized reaches.

Lower watershed: Channel morphology may remain unchanged as valley floor and stream bank vegetation still abundant and dams were located on the floodplains and backwater areas. However, complexity of vegetation communities changing as a result of beaver removal. Possible increases in flood peaks and decreases in flood durations due to greater channelization in upper watershed and periodic abrupt dam failures.

Second wave of large-scale Euro-American disturbances (i.e. grazing, agriculture, logging, milldams, ditches)

Upper and lower watershed: Vegetation removed from uplands, valley floor and stream banks. Wetlands drained deliberately or incise due to land use activities. Creation of points of flow convergence (roads, canals). Result is large increases in runoff and decreases the resistance of uplands, valley floors, and stream banks to erosion.

Upper watershed: Channelization expands and discontinuous channels begin to coalesce.

Drainage network transition II

Upper and lower watershed: Increases in available channel capacity as channels incise and widen. Water routed from upper to lower watershed during a storm event more rapidly. Streams and valley floors hydrologically disconnecting. Frequency of valley floor flooding in upper watershed decreases while the magnitude and frequency of flooding in the lower watershed increases. Stream ecosystem sensitivity to climatic variability increases, resistance to disturbance decreases and recovery rates after a disturbance slower

Current conditions (stream gages install during this period)

Upper and lower watershed: Channel-dominated. Streams and valley floors hydrologically disconnected. Reduced complexity, abundance and extent of the riparian zone. Loss of wetlands. Stream ecosystem sensitivity to climatic variability high, resistance to disturbance low and recovery after disturbance low.

Lower watershed: Increased frequency of higher magnitude floods.

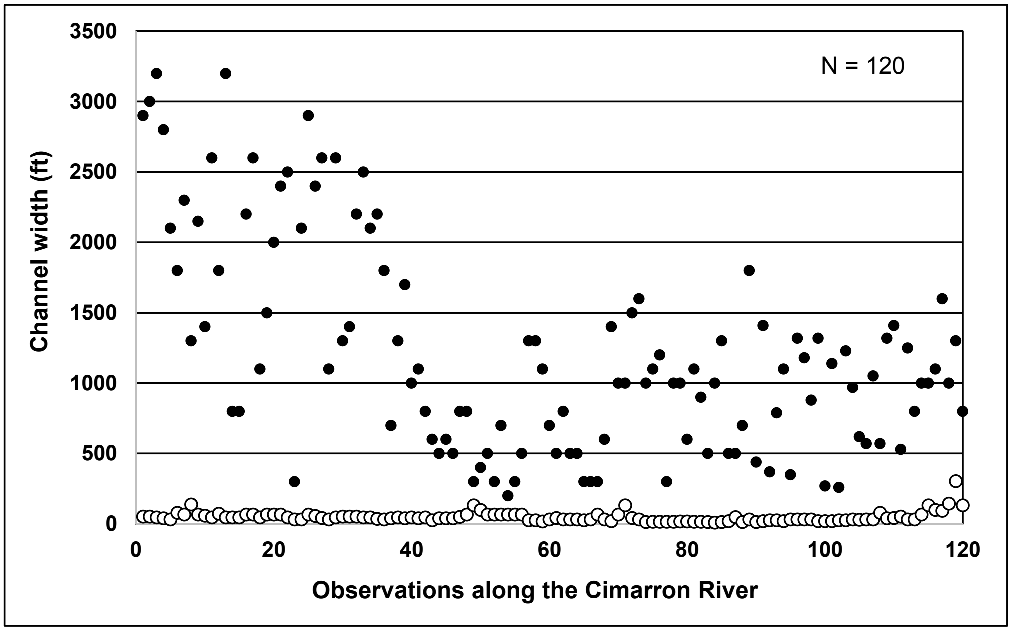

Figure 22—Changes in channel widths and variability along the Cimarron River in southwestern Kansas between 1874 and 1939. Open circles = 1874 widths. Solid circles = 1939 widths (figure generated using data found in Schumm and Lichty 1963).

From Present to Future

Climate change is bringing increased variability. The impacts on wild and human communities are already large and will only increase. As water is essential to all communities, we need to shift our landscapes from "water-sheds" to "water-stores" by allowing the missing parts to return and take up their places and functions on the landscape. Public lands are the ideal place to start beaver-driven stream system restoration. Public lands provide large contiguous areas where beavers can rapidly create vast ecologically complex water storage zones and diverse habitat with limited infrastructure conflicts. Large portions of these lands occur in the headwaters, making them uniquely situated to store water during times of abundance and then release it during times of drought. Because many of the streams are first- through fourth-order streams, they are the appropriate size for beavers and their dam complexes to rapidly restore stream processes and form in these areas.

The challenges inherent in recovering at least some of the stream-valley floor hydrologic connections and the water storage capability of stream systems without beavers become clear when examining the amount of channel incision and/or widening that has occurred (table 3) and volume of stream sediment eroded post-EA trapping. Bryan (1928a) estimated that the Rio Puerco in New Mexico, with a drainage area of roughly 6,220 mi^2 (USGS stream gage), had lost more than 394,882 acre-ft of sediment over a 42-year period as a result of channel incision and widening. On a smaller scale, an estimate of 7.2 acre-ft of sediment has been eroded from the 3.4 miles of headwater stream reaches studied by Fouty (2003). These drainages are located in southwest Montana and east-central Arizona and range from 692 to 18,775 acres.

The channelization of drainages across the North American continent resulted in the permanent removal of large volumes of sediment. Therefore, restoration of the stream-valley floor hydrologic connection, and the processes that result from that connection, requires abundant beaver dam complexes with their ponds in order to fill the void left by the eroded sediment. Where the amount of erosion prevents recovering the original stream-valley floor hydrologic connection, beaver dam complexes are still required to restore stream processes. However, in these cases these new beaver-dominated systems will be inset into the larger channels as is the case at Bridge Creek in eastern Oregon (Demmer and Beschta 2008; Pollock et al. 2007) and streams near Elko, Nevada (Swanson et al. 2015).

Two key factors prevent beavers from expanding in numbers and distribution. The first is recreational and commercial beaver trapping (Muller-Schwarze and Sun 2003), which removes not only existing beavers but their future progeny. An example of the cumulative effect of trapping on numbers is found in the data collected by Oregon Department of Fish and Wildlife and USDA Wildlife Services for the State of Oregon. The data listed 54,034 beavers reported killed between 2000 and 2015. Of this number, 83 percent (44,784) of the beavers killed were due to hunting and trapping with the vast majority from trapping (about 97 percent).

The second factor is insufficient food and building material due to past and current land uses, with browse pressure on riparian woody vegetation by livestock and wild ungulates being a key contributor on public lands. When livestock are the dominant browser, as was the case for streams near Elko, Nevada, changes in livestock management resulted in rapid improvements in the quality of riparian habitat (Swanson et al. 2015). The expansion of riparian vegetation and the absence of trapping allowed beavers in this area to expand their range such that during an extreme drought in 2012 the rivers with beavers still had water (Fouty, personal observation, July 15, 2012). Where wild ungulates are the browsers, work by Beschta and Ripple (2009, 2010) in Yellowstone National Park has shown the role that wolves play in decreasing elk and deer use of riparian areas leading to increased willows, aspen and cottonwoods. Here too beavers have expanded their range in response to improved habitat and no trapping (Smith and Tyers 2008). These studies show that sufficient food and building materials and the absence of trapping are required for beaver populations and their water storage benefits to expand. On public lands where both wild and domestic ungulates graze, changes in livestock management and expansion of wolf populations will be needed to reduce the browse pressure on key beaver food and building materials, along with the elimination of commercial and recreational trapping.

Conclusions

Separating out cause-and-effect relationships in fluvial systems is challenging because changes to their form and function are the result of many factors interacting over time and space. This chapter explored some of those factors in its examination of how EA beaver trapping altered the appearance and hydrologic behavior of stream systems and why the influence of beavers and beaver trapping were missed in the discipline of fluvial geomorphology until recently. It also examined how information gaps led to the development of relationships of process and form based on observations and measurements of channelized drainages and altered uplands that created conditions whereby water was rapidly shed from the landscape rather than stored and released slowly.

Given the magnitude of the historic changes and their hydrologic consequences, the scale of restoration and the rate at which it must occur is enormous if the impact of climate change on water availability, and the systems that depend on water, are to be minimized. Partnering with beavers to restore the water-holding capability of our stream corridors would rapidly dampen fluctuations in the abundance and scarcity of water and leave wild and human communities less vulnerable. Efforts will require broad public support and an integrated approach by State and Federal agencies given their respective areas of influence and impact. Scientists are in a position to help inform the discussions by sharing what we have learned about how past and current land uses affect the ability of the landscape to naturally store water for future use; however, our effectiveness will first require that we change the lens we have been looking through. Because the discipline of fluvial geomorphology has internalized and codified degraded systems as normal, our stream restoration efforts fall short. By placing these fluvial geomorphic relationships within their historic disturbance context, one that includes EA beaver trapping, new strategies, approaches, and partnerships emerge that are essential for restoration to successfully occur. This new lens reveals the essential role beavers play in this recovery process.

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