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# Compromised Rivers: Understanding Historical Human Impacts on Rivers in the Context of Restoration

*Ellen Wohl*[1]

ABSTRACT. A river that preserves a simplified and attractive form may nevertheless have lost function. Loss of function in these rivers can occur because hydrologic and geomorphic processes no longer create and maintain the habitat and natural disturbance regimes necessary for ecosystem integrity. Recognition of compromised river function is particularly important in the context of river restoration, in which the public perception of a river's condition often drives the decision to undertake restoration as well as the decision about what type of restoration should be attempted. Determining the degree to which a river has been altered from its reference condition requires a knowledge of historical land use and the associated effects on rivers. Rivers of the Front Range of the Colorado Rocky Mountains in the United States are used to illustrate how historical land uses such as beaver trapping, placer mining, tie drives, flow regulation, and the construction of transportation corridors continue to affect contemporary river characteristics. Ignorance of regional land use and river history can lead to restoration that sets unrealistic goals because it is based on incorrect assumptions about a river's reference condition or about the influence of persistent land-use effects.

Key Words: *river restoration; Colorado Front Range; historical land use*

## INTRODUCTION

River restoration is commonly undertaken to create a river that meets expectations with regard to its appearance and function or both. Expectations define a "reference condition," or the likely state of a river in the absence of human influence. These can be based on some hypothetical river condition assumed to exist prior to disturbance or on more idealized conceptions of how a river should look (Kondolf 1998, Kondolf et al. 2001). Restoration sometimes focuses on river function, restoring processes that provide self-sustaining aquatic or riparian habitat. Localized reach- or segment-scale restoration projects, on the other hand, are more likely to focus on the appearance of a river. In other words, the goal of river management is often the restoration of form rather than function.

An emphasis on appearance only can be misleading when the general public's conception of river health is based on a tidy appearance rather than on an understanding of ongoing river functions, such as floods that maintain the grain-size distribution of pool and riffle bedforms. A segment of river can meet many people's expectations of a healthy river if the water is clear and the stream banks are not rapidly eroding. However, the function of such a healthy-looking river can be highly compromised if flow and sediment are no longer moving downstream so that the habitats needed for diverse aquatic and riparian communities are not being maintained. This dichotomy between appearance, or form, and function gives rise to the concept of a compromised river. A compromised river is one that preserves a simplified albeit attractive form but has lost function because the hydrologic and geomorphic processes no longer create and maintain the habitat and natural disturbance regime necessary to ecosystem integrity.

The concept of an attractively tidy but less functional river is particularly important in the

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[1] Colorado State University

context of river restoration. That is because the public perception of a river's condition often drives the decision to undertake the restoration as well as the decision about what type of restoration is needed. If a river appears relatively attractive and healthy, the history of land use and the river responses that have directly influenced its current condition are unlikely to be explored. The net effect of most land use is to reduce the complexity and diversity of river form and function. At some point, these reductions cross a threshold, and the river is perceived as compromised and in need of restoration. This threshold can be very high. An alteration of the flow regime, a disconnection of the stream channel from the adjacent floodplain and hyporheic zone, a reduction of aquatic and riparian habitat diversity, and a loss of macroinvertebrate, fish, and riparian vegetation diversity can all be severe before the general public perceives that a river has lost function. Conversely, a river that is considered unattractive is more likely to be considered compromised and in need of restoration even if its appearance reflects the expected response to climatic and geologic conditions within the drainage basin. Braided rivers, or rivers along which large floods periodically reconfigure the channel and valley bottom, are more likely to be perceived as needing restoration even if their form and function have not been compromised relative to a reference condition. Public perception of a river often comes down to the variability and containment of the river. A dynamic and laterally unconstrained river is more likely to be perceived as needing restoration than a stable and confined river.

Delineation of a reference condition can be very difficult in a region in which most river systems have changed to some degree as a result of land-use patterns or in which land use has altered rivers for centuries. Under these circumstances, a reference condition is likely to represent an arbitrarily selected point in the ongoing history of human-induced change in rivers. A reference condition can be estimated based on (1) the river characteristics of unaltered but otherwise analogous rivers, if any are available; (2) the river characteristics that can be expected given the climatic and geologic features of the area (Fig. 1); or (3) the river characteristics recorded in historical records of the river prior to human influence and records of river changes resulting from land use. Regardless of how a reference condition is estimated, an historical knowledge of how land use changes rivers forms a critical component of restoration design. This historical knowledge provides a context for the causes, duration, spatial extent, and intensity of human-induced changes in a river (Petts 1989, Sear 1994, Kondolf and Larson 1995). When combined with a knowledge of the river characteristics of unaltered rivers or the river characteristics typical of the regional climate and geology, historical knowledge also helps to constrain what is possible in restoration. For example, rivers in a region with a history of placer mining may have been meandering prior to mining, and unaltered rivers nearby may still be meandering. However, restoration to a self-sustaining meandering form of mined rivers that are now braided may not be possible because of continuing high sediment yields from unstable mining tailings upstream.

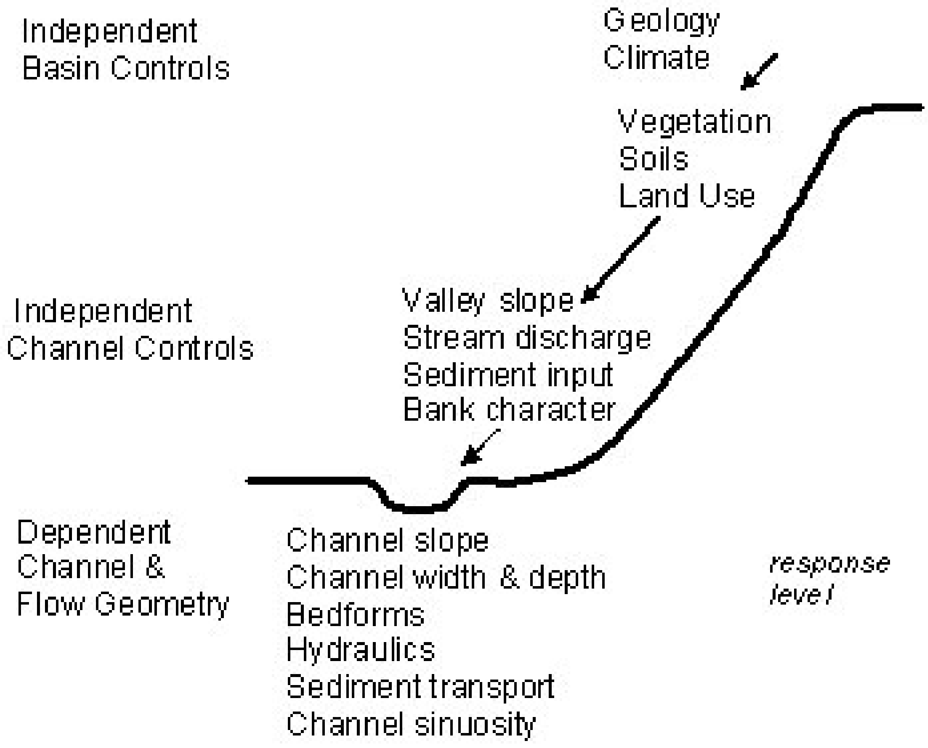
Rivers in the Front Range of the Colorado Rocky Mountains in the United States provide examples of how historical land-use activities have compromised the function of rivers that nevertheless appear pristine (Wohl 2001). These mountain streams have a suite of characteristics that result from the regional climate and geology as well as 200 yr of human land use. These characteristics, in turn, impose constraints on river restoration. Being aware of these constraints and working within them can result in effective river restoration that promotes self-sustaining diversity of form and function. Being ignorant of the constraints or attempting to override them is more likely to result in river restoration that fails to provide the benefits intended from the restoration, e.g., Uvas Creek in California (Kondolf et al. 2003).

The following sections summarize the physical context of rivers in the Front Range of Colorado, the history of human activities that have affected these rivers, the resulting change from reference conditions, and how knowledge of historical change can be used to determine rehabilitation priorities.

## THE PHYSICAL CONTEXT OF RIVERS IN THE COLORADO FRONT RANGE

The Front Range forms the easternmost part of the Colorado Rocky Mountains. Stretching approximately 275 km from north to south and 100 km from east to west, the Front Range is drained by streams of the upper South Platte River basin (Fig. 2). More than 10 streams flow from headwaters at about 4300 m elevation along the Continental Divide east toward the base of the range at 1520 m elevation.

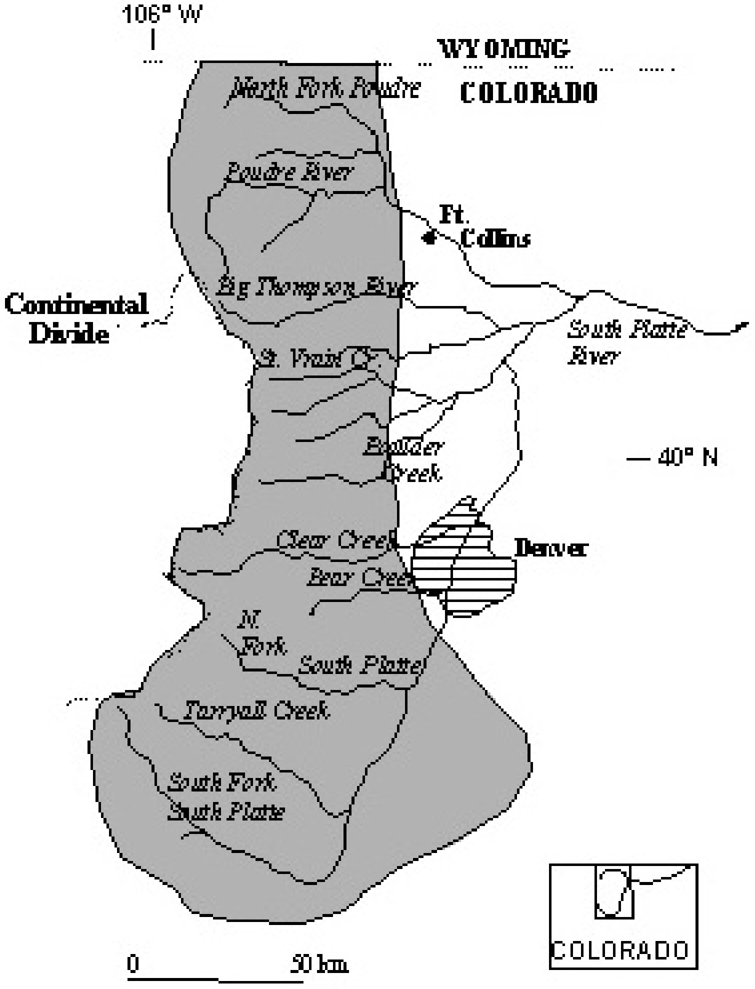
**Fig. 1**. Control and response variables.



There, beyond the mountain front, they join to form the South Platte River, which flows into the Missouri River and ultimately into the Mississippi River. Changes in climate, vegetation, and flow regime are associated with changes in elevation. Mean annual precipitation drops from approximately 100 cm at the highest elevations to 36 cm along the base of the range. Alpine vegetation in the headwaters gives way downstream to subalpine spruce-fir forest, montane pine forest, and eventually steppe vegetation. The major streams are perennial, with a snowmelt peak in late spring and early summer. Convective storms also generate summer rainfall that produces infrequent flash floods below approximately 2300 m elevation. These rainfall floods can generate a peak discharge that is as much as 40 times the size of snowmelt flood peaks (Jarrett 1989).

Rivers in the Front Range tend to have a very steep gradient (> 0.01 m/m) and a narrow valley bottom with a limited floodplain. Channels are likely to have step-pool or pool-riffle sequences, but channel and valley morphology is quite longitudinally variable because of downstream changes in geology, glacial history, and beaver activity. Most of the larger rivers alternate downstream between narrow, high-gradient canyons and wider, lower-gradient reaches that coincide with Precambrian shear zones. As a result of this longitudinal variability, valley segments are distinctly different in terms of gradient, substrate type, degree of lateral confinement, wood loading, frequency of disturbances associated with floods and debris flows and the response to them, and the diversity and stability of habitat. River form and function and the response to land-use patterns are thus most appropriately characterized at the scale of valley

**Fig. 2**. Location map.



segments or channel reaches of consistent morphology.

Most river segments have a coarse stream bed formed from cobble- to boulder-sized sediment. Widespread movement of the abundant sand and gravel underlying the stream bed does not occur during the average annual snowmelt flood. However, it does occur infrequently during summer rainfall floods. Only these floods generate sufficient stream power to mobilize the coarse-surface stream bed and to substantially reconfigure the morphology of the channel and the valley bottom. Flooding can also be exacerbated by a hill slope disturbance, such as a forest fire, that introduces large quantities of sediment into the river via debris flows and landslides. First- and second-order channels have more frequent and longitudinally extensive impacts from debris flows. Infrequently, with recurrence intervals of more than 100 yr, these flows can create localized deposits, such as partial levees, along the larger rivers. Rivers of the Front Range are thus normally stable with relatively low sediment loads, although they periodically exhibit dramatic responses to disturbance from floods and hill slope instability. These large, infrequent natural disturbances enhance the longitudinal differences among valley segments by causing erosion in steep, narrow-valley segments and enhanced deposition in wider, lower-gradient segments (Shroba et al. 1979).

Wood loading is relatively low even in the forested portions of the rivers, and spatial densities are commonly less than 0.15 pieces/m² of channel (Wohl, *unpublished manuscript*). First- and second-order channels have individual pieces of wood or jams of numerous pieces that partially span the channel. Both individual wood and jams create localized scour of the bed and bank as well as longitudinal steps. Upstream from these longitudinal steps, a wedge of sediment is stored. Wood is thus important in enhancing habitat diversity and channel stability in the smaller channels of the Front Range, but it is relatively rare and geomorphically insignificant in the larger channels. The relative paucity of wood in larger channels at least partly reflects a history of wood removal during the 19th and 20th centuries.

Organisms adapted to cold oxygenated water, coarse stream substrates, and turbulent flow are most common in the Front Range rivers. Macroinvertebrate abundance and species richness are low in the headwater reaches of these mountain streams and increase from the montane zone down to the foothills in response to increasing water temperatures and habitat diversity (Ward 1992). Fish diversity also increases downstream. Salmonids include native greenback cutthroat trout (*Oncorhynchus clarkia stomias*) in the stream segments at the highest elevation, and non-native brook trout (*Salvelinus fontinalis*), rainbow trout (*Salmo gairdneri*), and brown trout (*Salmo trutta*) in the middle- and lower-stream segments (Campbell et al. 1984, Raleigh et al. 1986). Other common species (U.S. Forest Service 1980) include western longnose suckers (*Catostomus catostomus griseus*), northern creek chub (*Semotilus atromaculatus atromaculatus*), fathead minnow (*Pimephales promelas*), and longnose dace (*Rhinichthys cataractae*).

## THE HISTORICAL LAND-USE PATTERNS IN THE COLORADO FRONT RANGE

People have lived in the Colorado Front Range for at least 12,000 yr (Eighmy 1984, Grant 1988, Benedict 1992), but there is no evidence that population densities or land-use patterns produced changes in the region's rivers until the first decades of the 19th century. Once people of European descent began to settle the region, numerous types of land use swiftly became widespread and substantially altered hillslopes and stream channels (Table 1). The following sections briefly summarize some of the effects of the earliest land-use patterns.

### Beaver trapping

Members of the 1804–1806 expedition of Meriwether Lewis and William Clark noted that beavers (*Castor canadensis*) were abundant in the western United States. After the conclusion of the expedition, these men helped open the region to fur trapping. Trapping quickly became so intensive that most of the beavers were trapped within two decades. John Charles Fremont rarely saw an active beaver lodge during his journey through the Front Range in 1842–1843, although he wrote of many abandoned beaver dams falling into disrepair.

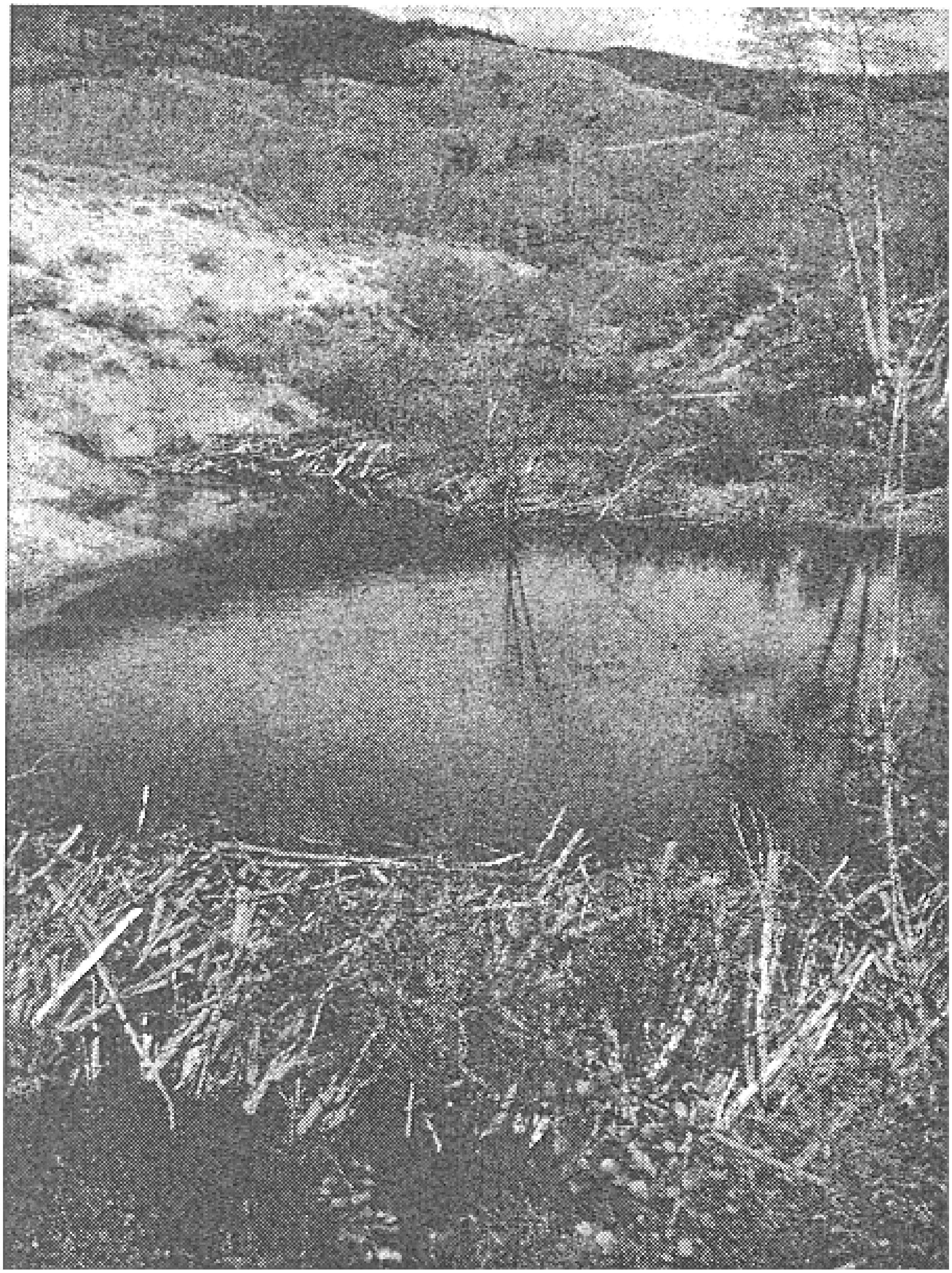
Beavers exert a strong influence on water and sediment movement along a river by building low dams of woody debris (Naiman et al. 1986, 1988). These dams create ponds that act as sediment traps, gradually filling to create swamp or meadow environments. The ponds and meadows also provide flood control during snowmelt floods, because, as the rising waters of a flood spread into the pond and across the valley bottom, they move downstream more slowly. The stepped profiles of beaver-influenced rivers, with narrow, deep, sinuous reaches above the ponds and shallower reaches of swifter flow below the ponds, maximize the diversity of riparian and aquatic habitats (Fig. 3).

From 1810 to 1860, tens of millions of beavers were trapped along rivers in the western United States. Once fur trappers discovered an area, the majority

**Table 1**. Chronology of historical and continuing land uses that affect rivers in the Colorado Front Range (Wohl 2001).

| **Land use** | **Period** | **Spatial extent** | **Influence on rivers** |
|---|---|---|---|
| Beaver trapping | Primarily 1815–1840 | All rivers affected | Removal of beaver dams increases flow velocity as well as stream bed and bank erosion. It decreases sediment storage, channel stability, and diversity. |
| Placer mining | 1859–1940s | Primarily Boulder, Tarryall, and Clear creeks, as well as the north and south forks of the South Platte River | Direct effects include disrupting the stream bed and bank structure, increasing sediment and channel mobility, altering the flow regime if diversion occurs, and introducing toxic contaminants such as mercury. Indirect effects include increasing the population, the amount of timber harvested, the number of transportation corridors, and the amount of sediment and contaminants entering the channels. |
| Railroad tie drives | 1860s–1890s | Poudre and Big Thompson rivers, lower St. Vrain Creek, and Boulder Creek | Effects include modification of the channels prior to tie drives, such as the removal of obstructions and naturally occurring wood, and the blocking-off of overbank areas, as well as scouring effects from pulses of water and wood. |
| Flow regulation, such as diversions and dams | 1859 to present | All rivers except North St. Vrain Creek and South Fork Poudre River | Effects include altering the magnitude, duration, and frequency of flows, as well as sediment transport, disturbance regimes, water chemistry, and water temperatures. |
| Timber harvest | 1859–1940s | All rivers affected | Effects include destabilizing hill slopes and increasing water and sediment yields to rivers. |
| Transportation corridors, such as roads and railroads | 1860 to present | All rivers except North St. Vrain Creek and South Fork Poudre River | Effects include increasing sediment to rivers because hill slopes are destabilized, unpaved roads erode, and traction sand and gravel are used on paved roads in winter. Transportation corridors also reduce the width of the floodplain and riparian corridors. |
| Lode mining | 1859–1980s | Rivers in the central and southern portion of the Front Range | Effects include increasing sediment yield from hill slopes and introducing toxic contaminants to rivers. |
| Urbanization | 1859 to present | Affects portions of all rivers but the North and South Fork Poudre River, Tarryall Creek, and South St. Vrain Creek | Effects include initially increasing water and sediment yield to rivers, followed by an increase primarily in water yield that introduces contaminants into rivers and constrains channel and floodplain space and mobility. |
| River recreation | 1909 to present | All rivers affected by introduced fish, the Poudre River by rafting | Fishing creates pressure on native species and promotes the introduction of other species. Whitewater rafting locally creates trampled streambanks with compaction, decreased infiltration, increased runoff and erosion, and damage to riparian vegetation. |
| Grazing | 1860 to present | Limited reaches along most rivers | Effects include removing riparian vegetation and compacting streambanks, bank erosion, wider and shallower channel cross-sections, finer stream bed substrates, increased nutrient input to rivers, warmer water temperatures, and reduced aquatic and riparian habitat. |

**Fig. 3**. Beaver dams.



of the beavers in the region were usually trapped within a few decades (Olson and Hubert 1994). With the removal of beavers, the beaver dams were breached, and some of the rivers incised rapidly into the accumulated fine sediment of the ponded stream reaches and turned them into gullies. Incised channels are characterized by larger, more flashy floods; increased sediment yield from unstable and eroding stream beds and banks; and less diverse habitat (Brayton 1984, Maret et al. 1987).

Although no one was keeping records of the response of Front Range rivers to beaver trapping during the early 19th century, we can infer what this response was by examining modern analogs. Contemporary studies indicate that flow downstream from beaver ponds contains 50–75% fewer suspended solids than that of equivalent stream reaches without these ponds (Parker 1986). When beavers were reestablished along Currant Creek in Wyoming during the 1980s, daily sediment transport decreased from 30 to 4 Mt (Brayton 1984). Local downstream channel slopes decreased, as did bank erosion during spring high flows, which was the main source of sediment in the river.

The net effect of beaver removal along rivers in the Front Range was probably a reduction in diversity and stability as channels locally incised, snowmelt flood peaks increased, flood-related sediment transport increased, and riparian and slow-velocity habitats were lost. However, the channel changes caused by the removal of beaver were probably much less substantial than those associated with changes in regional land use that began with wide-scale mining during the 1860s.

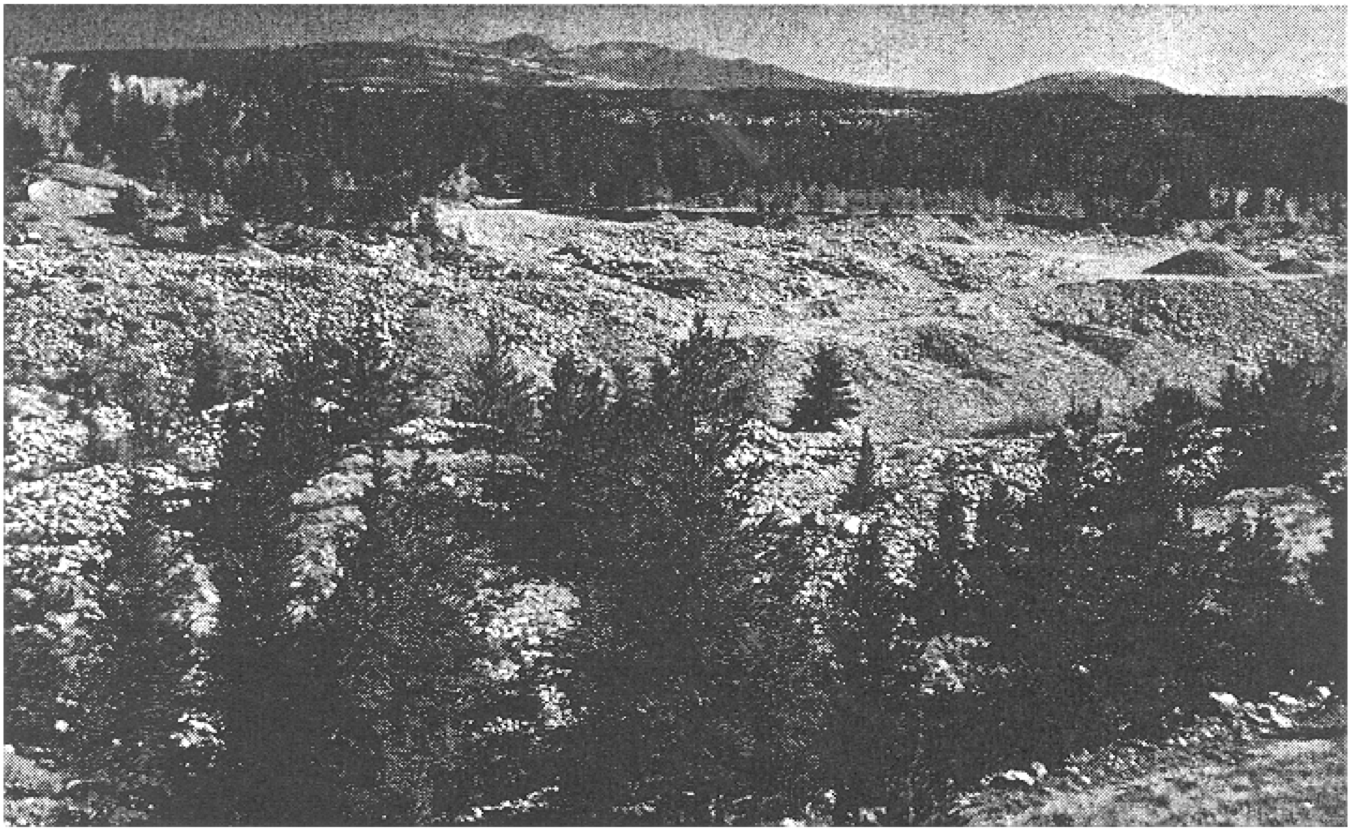
## Placer mining

The removal of placer metals such as gold and silver from stream bed sediments in Colorado began near Denver in 1859. Placer deposits were discovered throughout the Colorado mountains during the succeeding decades. Miners initially used hand-operated gold pans or shovels and sluices to process sediment and metals. An experienced miner using hand tools can process 0.4–0.6 m³ of sediment in 10 h. These methods were usually quickly replaced by hydraulic systems that used large hoses to direct pressurized water at the sediment deposits on the valley bottom. Two people operating a hydraulic system can process 2–4 m³ of sediment in 10 h. Commercial operators installed dredge boats at many sites. These boats were mineral processing plants: stream bed sediment was dredged up with large shovels, the placer metals were removed on the boat using physical separation or chemical separation via mercury amalgamation, and the remaining sediment was dumped back into the stream (Fig. 4). A dredge boat can process 6000–6600 m³ of sediment during 10 h (Silva 1986). The usual practice in either hydraulic or dredge-boat mining was to remove and process the stream bed sediment down to the bedrock contact and back to the valley side slopes.

The effects of placer mining on river form and function are threefold. First, the disruption of bed and bank sediment renders the sediment more susceptible to being moved by the river flow. This can cause downcutting of the river at the location of the mining or change a meandering river to a braided river (Hilmes and Wohl 1995). Smaller sediments are preferentially mobilized from the disturbed area and accumulate downstream. Downstream accumulation can reduce the river capacity and cause more flooding. Water quality is degraded by the increase in suspended sediment, which further degrades the aquatic habitat for a variety of species (Wagener and LaPerriere 1985, Van Nieuwenhuyse and LaPerriere 1986). The remaining coarse lag can be too large to provide spawning gravel for fish, whereas the finer sediment carried downstream can preferentially fill pools and cover spawning gravel downstream. The river at the mining site will remain less stable for decades after mining has ceased because the fine-grained bank sediment that once supported stabilizing riparian vegetation is gone (Hilmes and Wohl 1995). Placer mining along the mountainous headwaters of Colorado’s Clear Creek produced so much excess mobile sediment that an 1894 photograph taken from a balloon clearly shows sediment deposition along the creek well beyond the mountain front. This sediment, in turn, caused problems for newly built irrigation intake structures along the downstream portion of Clear Creek flowing through the Great Plains.

Second, toxic materials such as heavy metals or mercury used during mining are introduced to the stream and valley-bottom sediments. These materials are very persistent in the environment, as shown by the contemporary correlation between 19th century mining sites and the nation's worst toxic waste sites identified by the federal Superfund in the 20th century (EPA 1994). The most general

**Fig. 4**. Dredge-boat tailings.



effect of any pollutant is to reduce community diversity within and along a river (Mackenthun and Ingram 1966). Toxic materials interfere with the respiratory, growth, and reproductive functions of members of the entire river food web. The toxic materials can also act as a time bomb because they have an impact across time and space. The initial introduction is followed by processes of bioaccumulation and biomagnification over a period of years or decades. During biomagnification, toxic materials are not expelled by organisms but accumulate in fatty or other tissues. Any predator thus ingests all of the toxins accumulated by each of its prey organisms, and concentrations of toxins increase up the food chain. Longer-lived organisms can also continually ingest more of the toxin without expelling it, leading to bioaccumulation. The toxins may also be adsorbed onto clay or silt particles, lie buried in a sediment deposit, and be remobilized decades later by stream bed erosion or lateral channel shifting during a flood (Graf et al. 1991).

Third, placer mining indirectly affects rivers by altering the amounts of water and sediment entering the rivers. These alterations usually result primarily from the destabilization of the valley slopes as a result of timber harvest associated with the settlement of a region. Lumber is needed for sluices, flumes, stamp mills, mine timbers for lode mines, houses, and other buildings as well as for cooking and heating. Wood also fed the fires that once drove steam-operated stamp mills and smelters. After Congress passed the Free Timber Act of 1878 to protect forests by prohibiting the cutting of live trees on the public domain for commercial purposes, mining communities reacted by setting forest fires to create standing charcoal and dead trees that could then be legally harvested. Placer mining also redistributes sediment in valley bottoms, often removing lateral support at the base of hillslopes.

**Fig. 5**. Ties and saw logs.

Construction of roads, railroads, and buildings along hill slopes compacts slope surfaces and increases the weight over portions of the slopes. This destabilizes slopes further and increases sediment yield to rivers. Widespread deforestation and slope instability in the 19th century caused an increase in debris flows and landslides that was noted by observers at the time (Clark 1861, Tice 1872).

As with beaver trapping, the net effect of placer mining and associated activities in the Colorado Front Range was to reduce river diversity and stability. The contemporary activities of floating railroad ties to collection booms, regulating and diverting streamflow, and constructing transportation corridors further affected rivers. Together, these activities had an impact on almost every creek and river in the Front Range. They effectively overwhelmed the channel alterations associated with beaver trapping.

## Railroad development and timber demand

From the 1860s, when railroad companies began to lay tracks in the western United States, until the completion of most of the major commercial or mining routes in the 1890s, the construction of railroads placed a heavy demand on western timber resources. Most of the wood for the railroad crossties came from the mountains, and rivers provided a convenient route for transporting the ties downstream to collection points such as Fort Collins or Greeley. Millions of logs were rafted down the Front Range rivers. For example, more than 200,000 ties went down the Poudre River annually during the period 1868–1870 (Wroten 1956).

The mountain channels were altered to facilitate conveyance of the logs. Naturally occurring wood and large boulders were removed, overbank areas and marshes were separated from the main channel by dikes, and meanders were artificially straightened with cutoffs. The log masses themselves had the effect of a giant scouring brush as they moved down the channel (Fig. 5). Comparing rivers that had tie drives with analogous rivers that did not shows that the effects of the drives are still discernible 100 yr after the drives came to an end. Rivers that had tie drives have less diverse and less mature riparian vegetation. They also have wider, shallower channels with less pool volume and less naturally occurring wood (Young et al. 1990).

Secondary channels and overbank areas increase stream stability by providing places in which flow energy is dissipated during floods. They also increase habitat diversity by providing environments characterized by shallower, slower flows or ephemeral flow, increased hyporheic exchange, and storage of finer sediment and organic materials (Bayley 1991, Stanford et al. 1996, Kasahara and Wondzell 2003). The disconnection of secondary channels and overbank areas from the main channel as a result of channel modifications for tie drives reduces habitat diversity and channel stability along mountain streams.

In addition to the modification of channels to help move logs downstream, tie drives also removed naturally occurring wood from these channels. Numerous studies in the Rocky Mountains and coastal ranges of the United States have documented the important functions of such naturally occurring wood in mountain streams (Harmon et al. 1986, Richmond and Fausch 1995). Wood stores wedges of sediment and organic materials upstream and thus contributes to substrate diversity and habitat complexity at various scales. Wood creates pools either by causing a step in the channel profile and associated plunging flow or by directing the current toward a portion of the stream bed or bank. These pools form backwaters that provide critical summer and winter habitat and serve as refuges and rearing areas for fish. Wood also provides habitat and food for the stream insects on which fish feed. Removal of wood in streams during tie drives eliminated or severely reduced all of these functions.

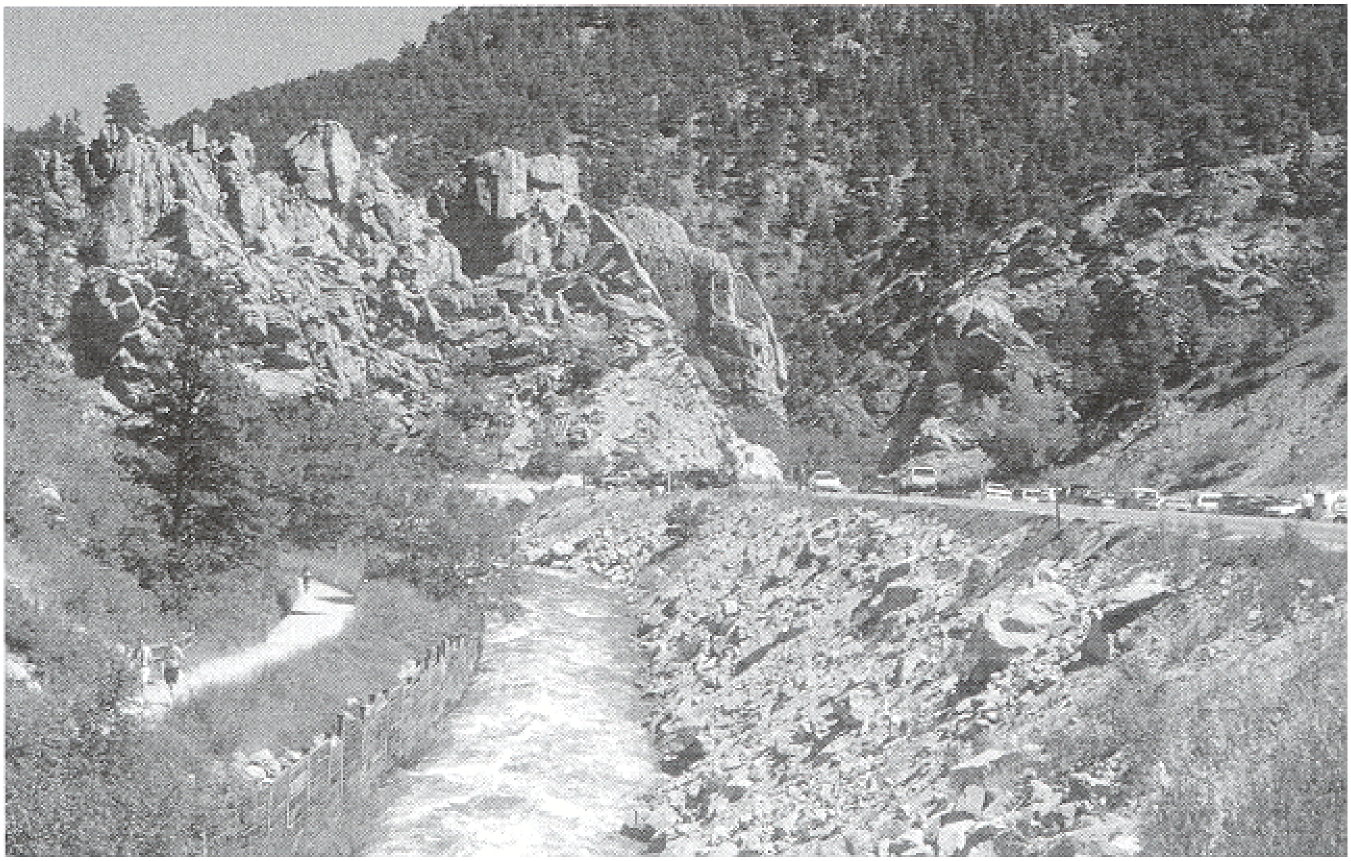
## Flow diversion and regulation

Flow diversions from rivers in the Front Range began with placer mining in 1859. The magnitude and extent of diversions increased dramatically during subsequent decades as irrigated agriculture and urban communities grew along the base of the Front Range. The lower Platte River of the western Great Plains was historically a broad, shallow channel with an extensive, largely unvegetated floodplain. The river had late-spring and early-summer floods when snowpack melted in the Rockies, but for much of the year the flow was shallow and turbid with suspended sediment. Reservoirs were built to store water for use late in the growing season, and water removed from the river was spread across the adjacent lands by a network of irrigation canals constructed between 1860 and 1900. As a result, the regional water table rose, the annual peak flow decreased, and base flow in the river increased. Riparian vegetation including cottonwood (*Populus deltoides*) and willow (*Salix* spp.) became established on the bars and banks of the river. This vegetation increased the hydraulic roughness of the river and reduced flow velocity, increasing sediment deposition to the point that the river began to narrow. Between the late 1800s and the first decades of the 1900s, some reaches of the Platte River decreased from 460 m to 90 m in width (Nadler and Schumm 1981). The formerly broad, open channel of the South Platte now meanders between thickly vegetated banks, and migratory birds that rely on open sandbars for feeding and resting are now restricted to short reaches of the river. Although flow diversions have generally had less physical effect on mountain streams in the South Platte basin, aquatic and riparian organisms have been affected by changes in the timing and magnitude of flow associated with diversions (Merritt 1999, Rader and Belish 1999).

## Construction of transportation corridors

Structures such as bridges or roadside slopes that impinge directly on a river channel can alter a river's form by creating a constriction. This constriction can increase flow velocity, which scours and coarsens the bed sediments (Fig. 6). The structures can also alter the characteristics of the water and sediment entering the river by changing the stability and permeability of adjacent hill slopes. During construction, disturbance of the hill slopes and river often results in a marked increase in the amount of

**Fig. 6**. Boulder Creek.



clay- to gravel-sized sediment moving in the river. This can continue after construction if the road is unpaved or if traction sand and gravel are used on the road during icy conditions. Erosion of a single unpaved road provided 25% of the basin's sediment in one 130 ha catchment tributary to the Big Thompson River (Balog 1977). Pools along Black Gore Creek near the corridor of the Interstate 70 highway were completely filled with traction sand and gravel coming from the road (Lorch 1998). Pollutants such as oil can also reach the river from the road surface.

Greater access to the river can result in an increased disturbance of the stream bed and the banks by people, mountain bikes, or off-road vehicles. These effects can be locally important in destroying riparian vegetation and compacting streambanks. This, in turn, reduces infiltration, increases runoff and sediment input to the stream channel, and alters the cross-sectional shape and stability of the channel. Intense recreational fishing, facilitated by road access, has also resulted in the widespread presence of exotic fish species that come mostly from hatcheries rather than from self-sustaining populations (Wohl 2001).

## CHANGE FROM REFERENCE CONDITIONS: COMPROMISED RIVERS?

Every river in the Colorado Front Range was affected by at least one of the land-use activities summarized in Table 1. Although a few were primarily affected by beaver trapping, most river segments were altered by the combined effects of beaver trapping, flow regulation, construction of transportation corridors, and associated recreation and urbanization. In the absence of detailed historical records predating the start of beaver trapping, the characteristics of the rivers prior to the 19th century cannot be known with certainty or precisely quantified. Reference conditions can be estimated by comparing rivers with multiple and continuing land-use affects to rivers with relatively few historical or contemporary alterations. In the Front Range, North St. Vrain Creek and the South Fork of the Poudre River are relatively unaffected by land use. Although beavers were trapped along both rivers and timber was harvested in their catchments, neither river had placer mining, flow regulation, extensive tie drives, roads, or railroads along its length. Both were also spared extensive grazing or recreational use. The characteristics of these rivers can thus be used to estimate the expected river conditions, e.g., pool volume, wood loading, and substrate grain-size distribution and stability, given the geologic and climatic setting of the Front Range.

Another approach to estimating a river's change from its reference conditions is to assess (1) ecological indicators, such as habitat quality and availability; (2) measures of biotic diversity, such as the distribution of macroinvertebrates; or (3) the presence of endangered species, such as the greenback cutthroat trout (*Oncorhynchus clarkia stomias*). Aquatic and riparian communities integrate the effects of changes in the physical and chemical environment and the influences of introduced species. The limited contemporary distribution of the native greenback cutthroat trout, for example, may reflect the presence of introduced brook trout as much as it does the loss of habitat diversity, pool volume, and wood in the rivers. Measuring the distribution of a species to estimate a river's change from its reference conditions requires a knowledge of the species' habitat requirements, such as the required substrate, flow, water chemistry, etc. The absence of the species when suitable habitat is available may reflect competition from introduced species. Detailed studies of the habitat requirements of various aquatic and riparian species native to the rivers of the Colorado Front Range are ongoing (Merritt 1999, D. Pepin, *personal communication*). Results to date suggest that some native species such as the cutthroat trout would have wider geographic distributions if they did not have to compete with introduced species, whereas other organisms, such as the river birch (*Betula fontinalis*; Merritt 1999, Merritt and Wohl 2006) or macroinvertebrates (Rader and Belish 1999), are compromised primarily because of physical changes such as altered flow regime.

The time interval since the last major natural disturbance is an important consideration when assessing reference conditions for rivers in the Front Range. The periodic disturbances of these rivers by flood or debris flow shows a certain degree of stochastic behavior. Thus, the most probable state of a river is best evaluated based on the average characteristics of a population of rivers over a short time interval or on the characteristics of a single river or catchment over a longer time interval.

## ESTABLISHING RESTORATION PRIORITIES

Despite a widespread reduction in channel diversity and stability as a result of beaver trapping, flow regulation, wood removal, and road construction, the rivers of the Colorado Front Range continue to support stable, if less abundant and diverse, aquatic and riparian communities. Most of the restoration recently undertaken or proposed in the region focuses on relatively short segments of the streams that are perceived to be unsightly, e.g., the Blue River in Silverthorne, Colorado (B. Bledsoe, *personal communication*). It also focuses on rivers that are unstable to the point of creating flood or sediment hazards, e.g., the Little Snake River near Slater, Wyoming (B. Bledsoe, *personal communication*), or that are compromised with respect to water quality or aquatic habitat or both, e.g., Boulder Creek in Boulder, Colorado (Ferguson 1991). Restoration attempts generally occur within constraints imposed by rapid growth in urban populations and recreational use, by the high demand for domestic water consumption, and by existing structures such as roads that impinge on the stream channel. Under these conditions, ignorance of regional land-use and river history can lead to restoration that sets an unrealistic goal. That is because this goal is based on (1) an incorrect assumption about a river's reference condition or (2) incorrect assumptions about the influence of persistent land-use effects. An example of the former would be a restoration project that attempts to stabilize a braided river on the assumption that the river is braided because human disturbance has increased sediment yields, when in fact the river was braided prior to intensive land use because of a naturally high sediment supply (Jaquette et al.

2005). An example of the latter would be a restoration project that attempts to restore fish habitat along a portion of a river still receiving heavy metals that leach from an upstream 19th century mining site.

Stepping back from reach-scale river restoration to questions of regional river management, a knowledge of historical land-use patterns and their associated effects on rivers is critical to understanding the contemporary "starting point." In the case of rivers in the Colorado Front Range, several years of drought combined with rapid population increases have revitalized proposals to build additional or larger reservoirs on several rivers. These proposals should be viewed in the context of a drainage network already seriously compromised by beaver trapping, timber harvest, placer mining, tie drives, existing flow regulation, and other land uses. Rivers have a history, and restoration or other management activities conducted in ignorance of this history are a disservice to river ecosystems and to human society.

*Responses to this article can be read online at:*
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