INHERITING OUR PAST: RIVER SEDIMENT SOURCES AND SEDIMENT HAZARDS IN COLORADO

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"...we must begin by recognizing that we cannot restore the state's rivers to pre-19th century conditions..."

AN OPEN LETTER ON RIVER SEDIMENT SOURCES AND SEDIMENT HAZARDS IN COLORADO

Rivers are one of Colorado's greatest resources. Ecologically-rich river corridors have provided routes of travel and sustenance for humans for thousands of years. River water has been vital to the State's agricultural, industrial, and municipal growth, and Colorado's rivers attract recreational users from around the world. At the same time, river processes may create hazards for human communities and aquatic organisms. Many people are aware of the hazards associated with floods such as the 1976 flood in Big Thompson Canyon or the 1997 flood in Fort Collins. River hazards may also involve the movement of sediment along the river, as when excess sediment accumulating in a reservoir reduces the storage capacity and expected life of the reservoir, for example.

This report summarizes the hazards associated with river sediment in Colorado. As population in Colorado continues to grow, conflicts over the management of rivers will also grow. Satisfactory resolution of these conflicts will require that everyone involved understands the basic processes of rivers and sediment movement, the history of river and land-use changes in Colorado, and the constraints that currently limit our abilities to mitigate sediment hazards. This report provides an introduction to these issues, and identifies actions that can be undertaken to reduce future sediment hazards associated with Colorado's rivers.

Sincerely,

Ellen Wohl
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PREFACE

Rivers are one of Colorado's greatest resources. Ecologically-rich river corridors have provided routes of travel and sustenance for humans for thousands of years. River water has been vital to the State's agricultural, industrial, and municipal growth, and Colorado's rivers attract recreational users from around the world. At the same time, river processes may create hazards for human communities and aquatic organisms. Many people are aware of the hazards associated with floods such as the 1976 flood in Big Thompson Canyon or the 1997 flood in Fort Collins. River hazards may also involve the movement of sediment along the river, as when excess sediment accumulating in a reservoir reduces the storage capacity and expected life of the reservoir, for example.

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THE PROBLEM

River channels are dynamic natural systems that are continually changing. A channel reflects to some degree all of the processes operating within its drainage basin. These processes are ultimately controlled by geology and climate, which together determine regional topography, soil development, the growth of vegetation, and the land-use practices of people living within the drainage basin (*Figure 1*).

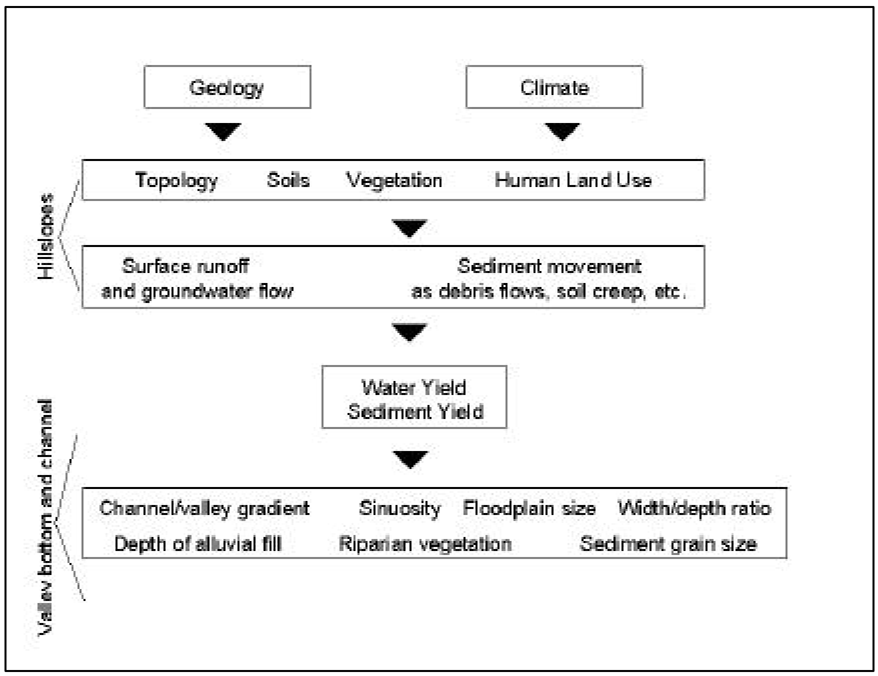


Figure 1. Schematic diagram of relationships among factors controlling sediment movement along rivers. Contaminants may move in association with water and/or sediment.

Hillslope features such as topography, vegetation, and land-use will influence the characteristics of water and sediment yield from the hillslopes to the channel. The movement of water and sediment along the channel will then depend on channel and valley-bottom geometry, but will also influence that geometry.

There are four basic processes by which sediment moves down a hillslope. Mass movements involve the rapid downslope motion of large aggregates of sediment. These movements include rockfall, landslides, debris flows, and slumps. In each case, the hillslope has become unstable, and the mass movement is a means of quickly redistributing mass.

Causes of mass movements include the addition of mass, as when mining tailings are piled on a slope; a decrease in particle cohesion, as when precipitation partially saturates a slope or seismic vibrations jar particles loose; or a removal of lateral or underlying support, as when an excavation for a roadway cuts away the toe of a slope.

Sediment may also move downslope as individual particles or small aggregates. Very intense rainfall on a slope of low permeability may create thin sheets of flowing water across the slope, and this water may carry sediment with it. The water may also concentrate into rills or gullies. The water's erosive force is greatly increased in these small channels. Both slopewash and rilling are particularly effective on sparsely vegetated slopes or on slopes that have been recently disturbed by something such as a forest fire. Finally, sediment may move very gradually downslope in cycles tied to freezing and thawing or wetting and drying. This process of soil creep may be effective even on densely vegetated slopes.

Once sediment enters a river channel, it may remain in place, or be transported downstream in dissolved, wash, suspended, or bedload. Dissolved load refers to material carried in solution in the water column. Dissolved load is high in drainage basins formed on rocks that are readily weathered and eroded, and in drainage basins where water moving slowly through the subsurface has time to react chemically with its surroundings before entering the stream channel.

Wash load is composed of fine sediments that are carried in suspension and are deposited along the channel margins to only a limited extent. Suspended load is also carried in suspension, but these coarser silt, sand, and gravel particles move sporadically, being carried some distance and then stored for a time in the channel bed. Bedload is composed of the largest particles, which move by rolling, sliding, or bouncing, and always remain in contact with the channel bed.

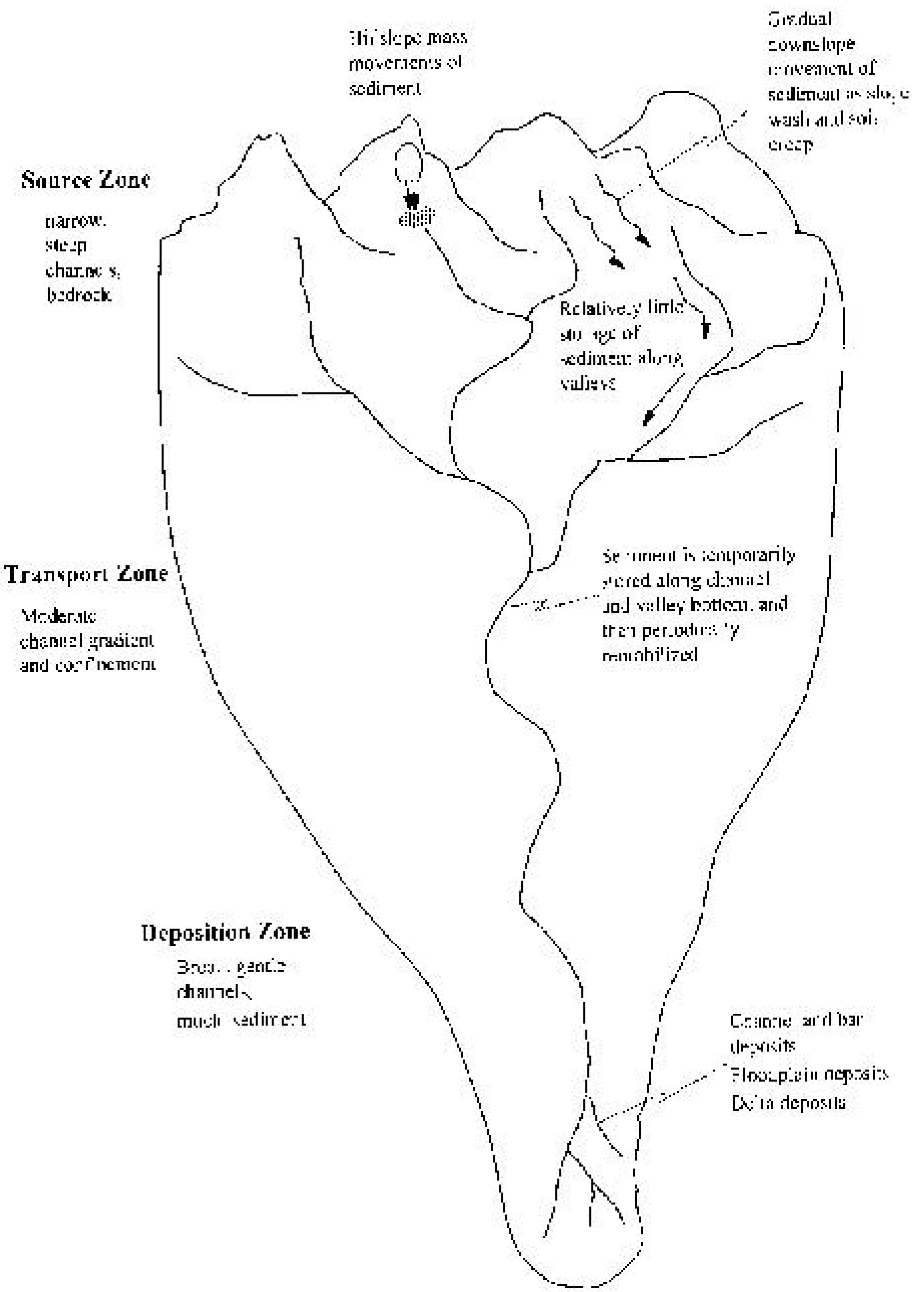
The grain size distribution and mode of transport of sediment will determine residence time within a river system: A clay particle that reaches a river from the hillslopes may be transported through the entire system in a few years, whereas a boulder that moves a short distance as bedload every few decades may remain in the river basin for millennia.

The relative importance of the different components in *Figure 1* varies with location in the drainage basin (*Figure 2*). The upper portion of a drainage basin is primarily a source for water and sediment. The channels in this source zone tend to be steep and narrow, with bedrock or boulders forming the channel boundaries. Sediment introduced directly to the channels from the steep hillslopes is moved rapidly downstream, with relatively little sediment storage along the valley bottoms. In Colorado, this source zone is best represented by the Rocky Mountains.

The central portion of a drainage basin is primarily a transport zone for water and sediment. Channel gradient decreases in the transport zone, and the narrowly confined valleys of the source zone give way to broader valleys with well-developed floodplains and larger volumes of stored sediment. Sediment in storage throughout the transport zone has a longer residence time than sediment in the source zone, although the downstream sediment is periodically mobilized. Many of the channels on the plains of eastern Colorado and the plateaus of western Colorado have the characteristics of channels in the transport zone.

The depositional zone at the downstream end of a drainage basin has very low-gradient channels flowing across very broad valleys. This zone is a sediment sink, where the finer sands, silts, and clays that have been transported from the uplands are stored for long periods of time along the valley bottoms. For many of the rivers originating in Colorado, this zone lies beyond the state borders, although some examples can be found in the San Luis Valley.

Because of the close connection between hillslopes and channels in the source zone, anything that alters the relationships diagrammed in Figure 1 is likely to affect river channels very quickly. A forest fire that destabilizes a hillslope may cause an increase in sediment yield to the channel during the next rainfall. If the increase in sediment yield is sufficiently large, pools along the channel may fill with sediment, destroying fish habitat, and riffle gravels used for spawning may be become covered with silt.



♦♦ ***Figure 2. Schematic drainage basin illustrating natural sediment sources and sinks. This llustration may be applied to any scale of drainage basin.***

In contrast, changes in hillslope processes must be progressively more widespread, severe, or long lasting to affect channels in the transport and depositional zones. These channels integrate processes operating over a much wider area, and there is a time lag before changes in water and sediment yield reach these channels. The increase in sediment yield following the forest fire in the upper basin may not be substantial enough to affect channels in the transport zone if the sediment is gradually redistributed along the upper-basin channels. A regional shift in climate, however, such as occurred in the central and western U.S. during the 1930s, may be sufficient to cause a change in channel processes throughout a drainage basin.

Because hillslopes and channels are dynamic systems, they constantly adjust in response to various types of disturbances that affect different levels of *Figure 1*. Examples of disturbances that alter water and sediment yield to channels are forest fires, intense rainstorms or seasonal variability in precipitation, rockfalls, timber harvest, grazing, the raising of crops, road construction, and urbanization. Each of these factors influences how precipitation falling on a hillslope moves down that hillslope into a channel, and how that moving water carries sediment with it.

Disturbances that affect in-channel processes include floods, debris flows, dams and flow regulation by drop structures or diversion structures, and placer mining. Different portions of the drainage basin may respond differently to these disturbances. A dramatic increase in water and sediment yield may be necessary to change the gradient of headwater channels, which are formed in very resistant bedrock and large boulders. An increase of sediment may cause loss of pool volume in these channels, however, and a change in the size of the sediment forming the channel bed. In contrast, an increase in sediment yield to the lower portions of a drainage basin may result in a shift from a meandering channel to a braided channel with numerous flow paths between rapidly shifting bars.

Hazards associated with sediment

The movement of sediment from hillslopes and along channels creates a hazard when it adversely impacts humans and their infrastructure, or something which humans value, such as fish habitat. These hazards may result from processes that would occur in the absence of human activities, or they may result directly from those activities. Timber harvest, for example, may have the same effect as a forest fire in that it results in greatly accelerated movement of sediment to river channels.

Sometimes human structures mitigate the hazardous effects of natural processes, as when the dam at Strontia Springs stored sediment mobilized by the 1996 Buffalo Creek fire. The effects of human activities differ from those of natural disturbances in that, with the exception of climate variability or massive wildfires, human-related disturbances are more likely to affect an entire drainage basin, and to create unforeseen hazards through their cumulative impact. Water diversion and flow regulation in the South Platte River drainage basin, for example, are so extensive that they affect the ability of many channels to redistribute sediments contaminated by agricultural runoff. Because of these unforeseen consequences of human activities, and because of the continuing hazards posed by natural disturbances to sediment movement, it is vital to develop an integrated approach to hazard mitigation that recognizes hillslope/channel and upper/lower basin linkages.

Sediment hazards in Colorado take three basic forms:

- excess of sediment,
- decrease of sediment, and
- contamination of sediment.

These hazards may be in reference to pre-human-settlement levels. For example, widespread urbanization and an increase in paved area within a drainage basin may so decrease sediment yield to a channel that the channel banks begin to erode, endangering structures near the banks. A concentration of grazing animals in the riparian zone may lead to loss of riparian vegetation and decreased bank stability, which in turn results in more sediment entering the channel, leading to loss of fish habitat. The hazards may also be in reference to what is desired for a specific use of the channel, as when an increase in sediment following a forest fire causes siltation and damage to irrigation intake structures, or results in lost storage capacity behind a dam, thus shortening the expected life of the structure.

The hazards associated with river sediment may be very local in scale, or they may affect a large portion of a river's drainage basin. Grazing along the riparian corridor, for example, may affect only a few miles of river at and immediately downstream from the grazed portions of the river. Once the grazing animals are removed, the river may recover within a few years. At the opposite extreme, toxic metals introduced into a river in association with mining may be transported tens to hundreds of miles downstream from the mining site, and may persist as dangerous contaminants for centuries after mining has ceased.

Excess of sediment generally implies that flow in the channel is not capable of transporting all of the sediment supplied, resulting in a change of channel pattern, loss of specific channel features such as pools or spawning sites, filling of the channel and overbank flooding, or filling of a reservoir. Decrease of sediment implies that flow in the channel is capable of transporting more sediment than is being supplied. Consequently, the excess flow energy will be expended on channel erosion, resulting in bank collapse, bridge-pier scour, channel downcutting, and other changes.

Sediments may be contaminated by materials toxic to humans and aquatic organisms, such as agricultural and urban pesticides or mining leachates. Sediments may also be contaminated by excessive levels of nutrients such as urban and agricultural phosphorus which create algal blooms that reduce dissolved oxygen and harm fish populations, a problem in many of the reservoirs in Colorado used for human recreation.

In order to mitigate these sediment hazards, we have to first understand the controls on, and processes of, sediment movement on hillslopes and channels. Then we must understand how human actions alter these controls and processes, because there are today very few places in the State of Colorado where human actions do not play a role. In addition, it is vital to recognize that sediment transport, deposition, and erosion are natural processes that will always occur along rivers. Finally, we must understand the societal, legal, environmental, and scientific constraints on our ability to modify human actions and to mitigate sediment hazards.

This report will summarize these three last issues specifically in reference to the State of Colorado. The report provides only a brief, non-technical introduction to a highly complex problem. Supplementary references that can assist the reader in gaining further understanding are listed at the end of the report.

THE RIVERS OF COLORADO

The State of Colorado includes seven major water basins with 105,600 miles of rivers and 3,260 lakes, reservoirs, and ponds. The State can be divided into three physiographic provinces; the eastern plains, the central mountains, and the western plateaus and canyons (*Figure 3*). Each of these provinces has distinctive traits of geology, climate, soils, vegetation, topography, and land use that in turn produce distinctive types of river channels.

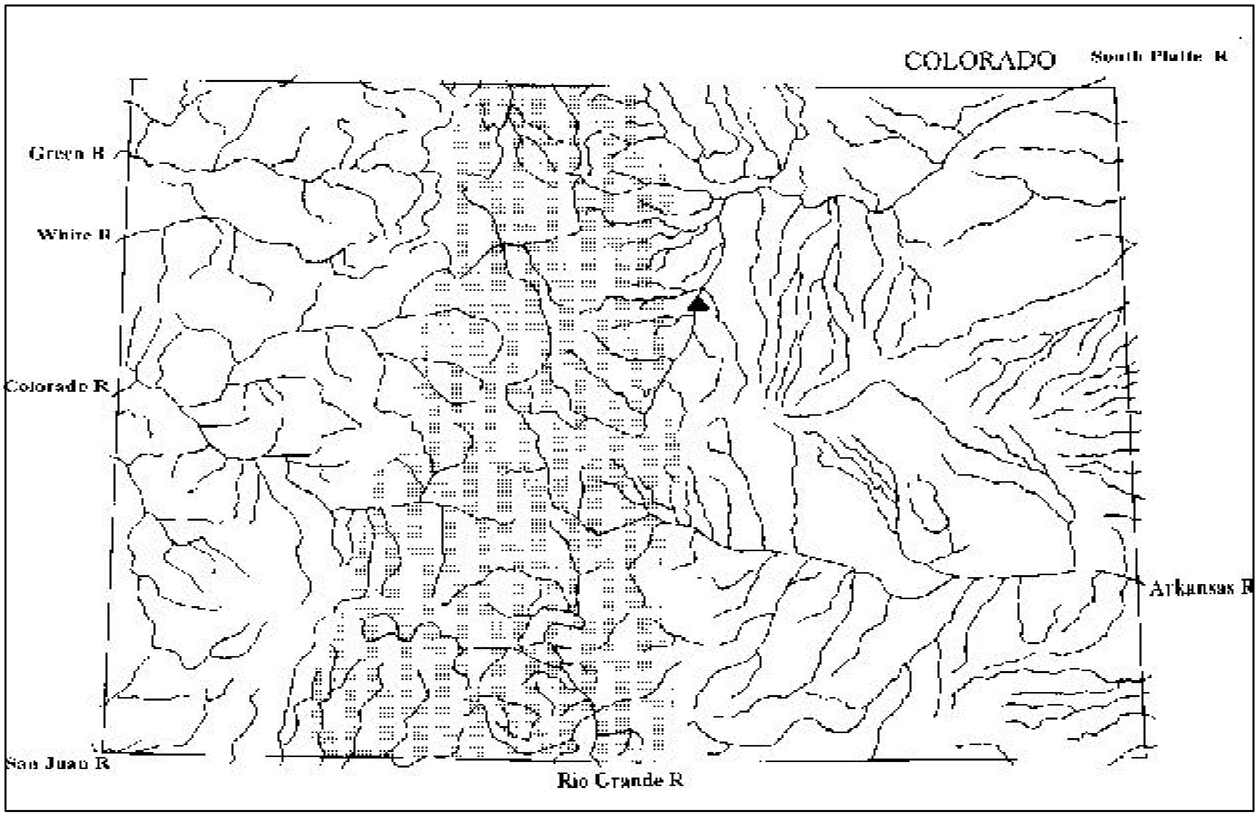


Figure 3. The State of Colorado, with major drainage networks and the three physiographic provinces. The eastern plains are the white band at the right of the fiture; the mountains are indicated by the shaded band in the center of the figure; and the western plateau and canyon region is the white band at the left of the figure. The triangle at the western edge of the plains represents the City of Denver.

The plains rivers

The larger rivers of Colorado's eastern plains originate in the Rocky Mountains and are dominated by the seasonal snowmelt cycle. Smaller tributary channels that originate on the plains flow mainly in response to summer rainfall. Prior to European settlement in Colorado, the plains rivers had strongly varying flow during each year, with very little discharge during the dry times of the year and large floods in late spring and summer. The channels were broad and sandy, with low banks, sparse woody vegetation, and many smaller channels between shifting sand bars. Abundant sediment was carried along the channels.

The old expressions of the Platte River as “a mile wide and an inch deep”, and “too thick to drink but too thin to plow” aptly describe the character of the plains rivers. A warm water fish fauna dominated by red shiner, sand shiner, fathead minnow, longnose dace, white sucker, plains killifish, and green sunfish lived in these channels. The channels had small clumps of green ash, plains cottonwood, box elder, and willow growing along the banks.

The sediment carried by the plains rivers was ultimately derived from weathering and erosion of the Rocky Mountains, and from sediment carried into the drainage basin by wind, but much of the sediment was locally derived from the channel bed and banks, the river’s floodplain, and the nearby hillslopes.

Following the intensive settlement of the plains that began with the 1859 gold rush, land-use practices so altered the water and sediment flows along the plains rivers that the channels underwent what scientists call “river metamorphosis” — a thorough change in channel functioning and pattern. The primary influence was flow regulation and diversion, which reduced seasonal flood peaks and increased dry-season base flow in the channels. As irrigation water that was diverted and spread across agricultural fields filtered into the subsurface, regional water tables rose.

These changes in surface and subsurface water movement facilitated the growth of riparian (stream-side) vegetation. As the vegetation along the channel banks grew thicker and erosive floods decreased, more sediment moving along the channel was trapped on the banks, and the channels gradually became narrower. Channels that in the 1800s had been 1400 ft wide and braided, had by 1980 narrowed to only 300 ft wide, and meandered between densely wooded banks.

The amount of sediment carried by the plains rivers decreased as dams built across the rivers served as large settling tanks, and the smaller seasonal high flows had less energy to carry sediment. The water in the deeper, shaded channels became cooler than it had been historically, and the native fish were displaced by species such as common carp, largemouth bass, bluegill, black crappie, and yellow perch that were tolerant of the new conditions. Wildlife traditionally confined to the eastern US spread westward along these river corridors, so that white tail deer and eastern bluejays reached Colorado. The exotic riparian species tamarisk, Russian olive and Siberian elm have also invaded the river corridors, displacing some of the native species and increasing the stability of the river banks and islands (*Figure 4*).

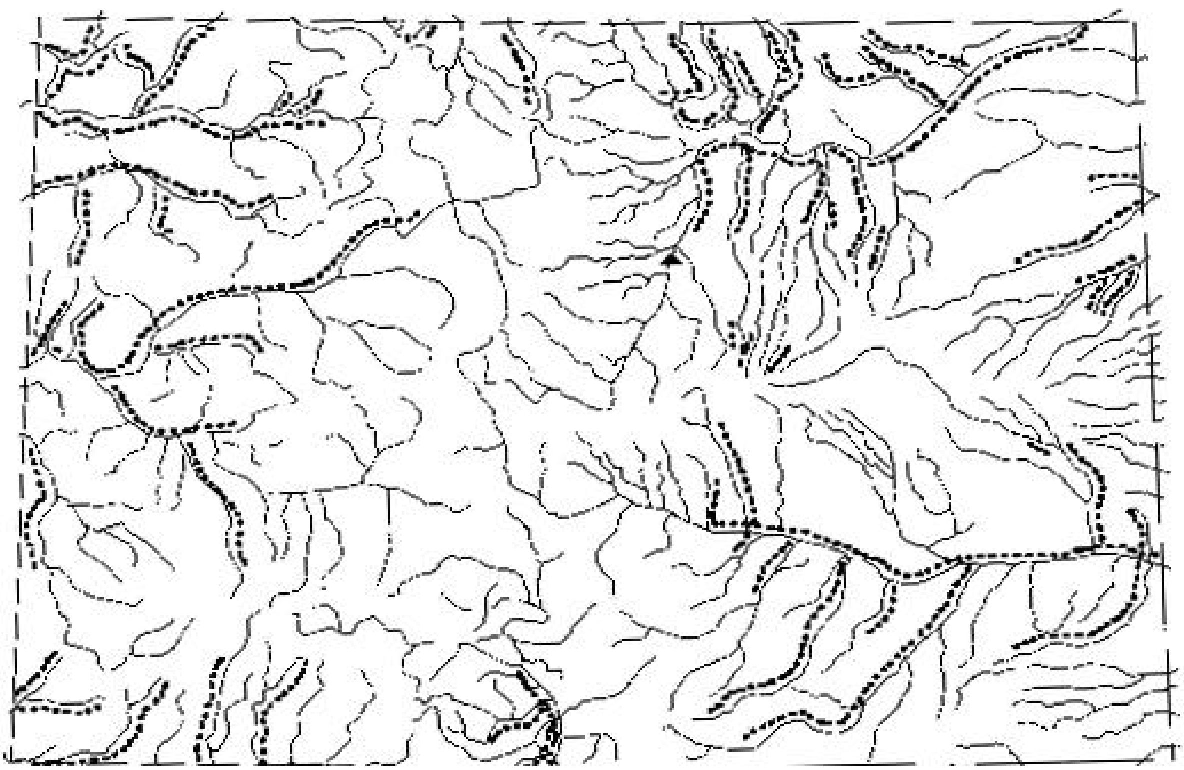


Figure 4. The State of Colorado, dotted lines paralleling watercourses indicate the extent of the exotic riparian tree tamarisk, as of 1988.

The mountain rivers

The rivers of Colorado's central mountains are largely driven by snowmelt and have peak flows in late spring or early summer. Superimposed on this seasonal cycle are flash floods generated by summer thunderstorms below approximately 7600 ft in elevation. These flash floods can be particularly destructive, as in the case of the 1976 Big Thompson flood. The mountain rivers tend to be steep and rocky, closely confined by valley walls. The water is cold and clear, with very little sediment transport except during floods, and the native aquatic insects and fish have adapted to these flow conditions.

Greenback cutthroat trout, Colorado River cutthroat trout, Rio Grande cutthroat trout, mountain sucker, and Rocky Mountain whitefish are native to the mountain channels, but they have been largely displaced by introduced rainbow, brook, and brown trout. Along the channels grow narrowleaf cottonwood, river birch, alder, red osier dogwood, chokecherry, and willow. Sediment movement along the mountain rivers is very closely tied to hillslope processes, because debris flows and rockfalls commonly introduce sediment directly from the steep canyon walls to the river. Many of the individual particles of sediment are so large that they remain stable in the channel, moving only during very large floods. Relatively little of the river's sediment load is derived from the surrounding valley bottom.

Like the plains rivers, the mountain rivers of Colorado have also been significantly affected by human activities during the past two centuries. By removing millions of beavers during the 1820s-1840s, the fur trappers also removed the small dams maintained by the beavers. These log dams, and the ponds behind them, slowed the passage of floods, trapped some sediment, and created a more diverse environment for aquatic and riparian organisms.

Starting in 1859, placer and lode mining had a much more substantial effect on the channels. Miners commonly stripped the channel sediments to bedrock in productive mining regions, in the process greatly increasing sediment mobility and consequently reducing water quality and killing many aquatic organisms. The increase in sediment transport was so severe that irrigators on the plains portion of these rivers complained that their intake structures were being buried by sediment. The miners introduced heavy metals that have persisted in the stream sediments long after mining ceased, creating toxic contamination of these sediments.

The need to transport people and goods between the mountains and other regions lead to widespread road and railroad construction, and the disruption of hillslope vegetation and soils associated with these activities caused a further increase in sediment to the mountain rivers. Many of the ties used in construction of local railroads and transcontinental lines such as the Union Pacific came from trees cut in the Front Range. The timbers were stacked beside the rivers during the winter, and then rafted downstream to towns such as Ft. Collins or Greeley during the spring flood. The rafting of hundreds of thousands of logs down a mountain river acted like a mammoth scouring brush on the river; channel width increased, pool volume decreased, the channel bed was disrupted and sediment mobilized, and the riparian vegetation was damaged or destroyed.

Simultaneous with these changes, the growing human communities at the foot of the mountains were storing and diverting water from higher and higher in the drainage basins, causing changes in flow magnitude, timing, and duration. The result of all of these impacts has been a shift toward more uniform rivers. The abundant woody debris and beaver dams that used to create deep pools have given way to channels with smaller pools and greater lengths of runs or riffles. The changes in flow regime and channel form, along with competition from introduced species, has lead to endangered status for the native greenback cutthroat trout, and has caused a general decline in the abundance and diversity of both riparian and aquatic species.

The plateau and canyon rivers

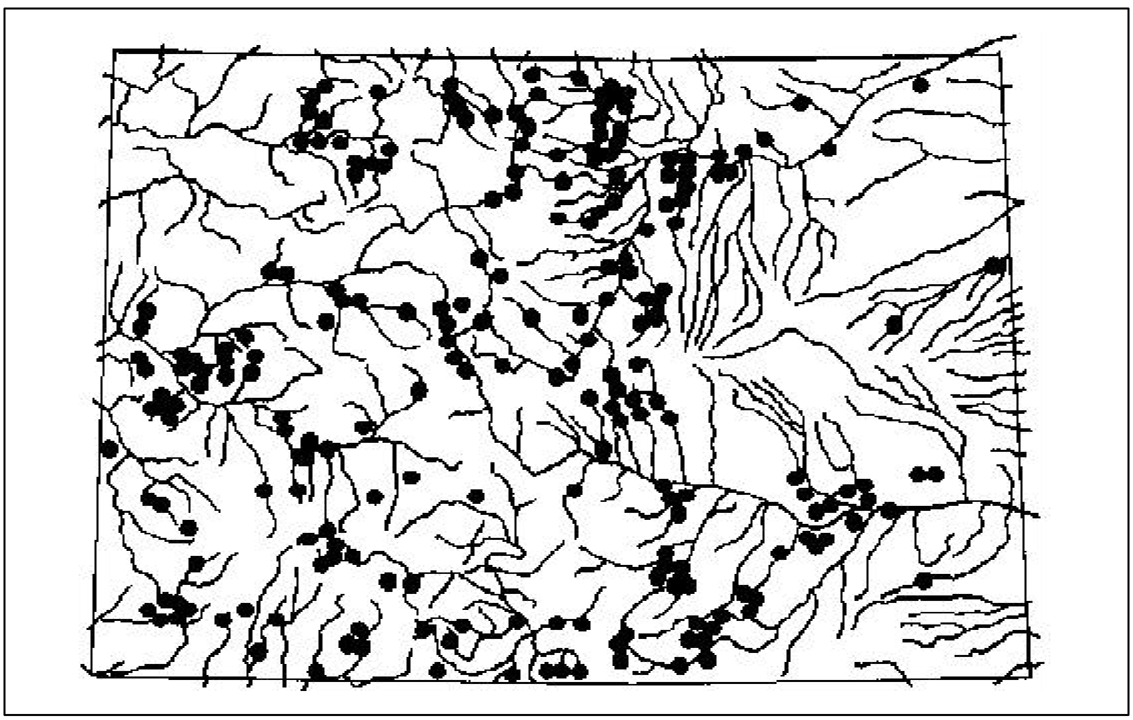
The rivers of Colorado's western plateaus and canyons are similar to those of the eastern plains in that flow in the larger rivers is dominated by snowmelt from the mountains, whereas the smaller, ephemeral channels may be driven by rainfall from summer thunderstorms. The rivers of western Colorado are commonly confined by bedrock canyons that may be very steep and narrow, or may have a broad valley bottom covered by a thick veneer of sediment. Many of these canyon rivers have alternating pools and rapids, with the coarse sediment that forms the rapid coming from rockfall or from debris flows and floods down the tributary canyons. The water of the western rivers was historically warm and turbid with sediment, supporting a warmwater fauna of Colorado squawfish, bonytail chub, razorback sucker, humpback sucker, roundtail chub, speckled dace, flannelmouth sucker, bluehead sucker, and mountain sucker. These rivers also supported large stands of Fremont cottonwood, sandbar willow, peachleaf willow, and hackberry along the valley bottoms.

During the past 100 years, and particularly since the 1930s, flow along the western rivers has been extensively regulated by a series of large dams and diversions, such as Williams Fork Reservoir on the Williams Fork River, Green Mountain

Reservoir on the Blue River, Flaming Gorge Dam on the Green River, or Blue Mesa Reservoir on the Gunnison River. Contemporaneous with these changes were the accidental and deliberate introduction of non-native fish species including red shiner, northern pike, fathead minnow, channel catfish, longnose sucker, white sucker, common carp, smallmouth bass, green sunfish, black crappie, and sand shiner. The fourteen native Colorado River fish now have to compete with more than forty non-native species.

Also introduced was the non-native riparian plant tamarisk. Tamarisk is a particularly tenacious and successful plant that quickly colonizes new river-bank deposits and grows in dense stands that effectively trap sediment. Combined with the decrease in flood peaks following flow regulation, the spread of tamarisk has caused dramatic channel narrowing and a decrease in sediment load along some western Colorado rivers. Between 1870 and 1970 the Green River in Dinosaur National Monument, for example, narrowed by up to 55% of its former width. The water released by the large dams is cold, clear, and poor in nutrients. This change in water quality, combined with changes in the magnitude, timing, and duration of flow, the introduction of non-native species, and the loss of floodplain habitat, has caused the Colorado squawfish, the humpback chub, and the razor-back sucker to decline to the point that they must be listed as endangered. The native cottonwood groves are also threatened along many of the western rivers because of the competition from tamarisks and the change in channel dynamics associated with flow regulation.

Many of Colorado's rivers have undergone substantial changes since 1800 as a result of human activities (*Figure 5*). In some instances, the effects of these activities completely dominate the natural controls on sediment movement into and along the rivers. However, there remain sediment issues that are unique to each of the three physiographic provinces because of the geologic and climatic characteristics of those provinces. The next section of this report highlights a series of examples of sediment hazards in Colorado.



♠♠ ***Figure 5. The State of Colorado. Black dots indicate dams and reservoirs in the state, including very minor reservoirs.***

SEDIMENT HAZARDS IN COLORADO

Most of the case studies of sediment hazards highlighted in this section somehow involve human impacts on sediment processes. Human activities may indirectly affect river channels if the movement of water and sediment from hillslopes to channels is altered. Examples of such activities include timber harvest, crops, grazing, road construction, and urbanization. Human activities may also directly affect river channels by altering the flow of water and sediment along the channel, as results from dams, flow diversions, channelization, beaver trapping, or placer mining. These types of effects have occurred on river channels throughout Colorado.

Examples of hazards associated with excess sediment

(1) North Fork Poudre River, Larimer County: The draining of Halligan Reservoir in late September 1996 was accompanied by the release of approximately 7,000 cubic yards of clay to gravel sized sediment that had accumulated in the reservoir. Flow from the drained reservoir was shut down immediately after the sediment was released, allowing the sediment to settle along more than 10 miles of river downstream from the reservoir. The sediment covered riffles with a thin veneer and filled pools up to 14 feet deep (*Figure 6*). The immediate effect of the sediment

Figure 6. Looking upstream along the North Fork Poudre River in October 1996, following the sediment release from Halligan Reservoir (approximately 500 yards upstream from this view). The portion of channel in the foreground is a pool that was up to 14 feet deep prior to the sediment release.

release was a massive kill of aquatic organisms; the Colorado Division of Wildlife (CDOW) estimated 4,000 dead fish along the ten miles of channel immediately downstream from the reservoir. Over the longer term, the continuing presence of excess fine sediment along the channel has inhibited re-colonization by aquatic insects and fish. CDOW is now proposing to re-stock fish along a river that had supported a self-sustaining population prior to the sediment release.

(2) Sheep Creek (northern Poudre River drainage basin), Larimer County: Segments of the Sheep Creek banks have been fenced as grazing exclosures since 1956 so that the impact of different intensities of grazing can be evaluated. Comparison of grazed and ungrazed segments immediately adjacent to one another along the channel indicates that grazing cows trample the stream banks and destroy riparian vegetation, causing an increase of fine sediment in the channel. This excess fine sediment preferentially accumulates in pools, reducing fish habitat. The fine sediment also infiltrates the riffle gravels used by fish for spawning, with the result that the flow of water and oxygen past the fish eggs is reduced, and the embryos die. The removal of over-hanging vegetation and the trampling of the banks creates a wide, shallow channel with warm water, whereas most of the aquatic organisms living in channels such as Sheep Creek are adapted to cold, clear water with overhead cover that protects them from predators (*Figures 7 and 8*).

Figure 7. Looking downstream along a portion of Sheep Creek that is excluded from grazing. The channel is densely shaded by willows, and is approximately 12 feet wide.

(3) Buffalo Creek, Jefferson County: Following a forest fire that burned 2,000 acres of the Buffalo Creek drainage in May 1996, massive sediment yields came from the burned hillslopes during a series of rainstorms in June and July 1996 and 1997 (*Figure 9*). The highly weathered granite underlying the hillslopes provided a source of abundant sediment once the vegetation was removed during the fire. The summer rainstorms caused 9 floods that were greater than the 100-year flood (pre-fire conditions), as well as numerous smaller floods (R. Jarrett, U.S. Geological Survey, unpub. report). Sediment associated with the floods and debris flows filled channels and culverts, buried houses and other structures along the channel banks, and caused several million dollars in public and private property damage. Two lives were lost during the 12 July 1997 flood. The combination of excessive sediment and large woody debris that accumulated downstream from the burned area, in Strontia Springs Reservoir, reduced water quality in the reservoir and threatened reservoir operations to the point that the City of Denver flushed sediment from the reservoir three times between September 1996 and September 1997. Nutrients contained within this sediment introduced thousands of tons of nitrogen and phosphorus into Chatfield Reservoir, downstream from Strontia Springs, and affected water quality in Chatfield.

Figure 8. Looking across the channel of Sheep Creek immediately upstream from the view in Figure 7. This portion of the channel is open to cattle grazing. The channel here is approximately 30 feet wide.

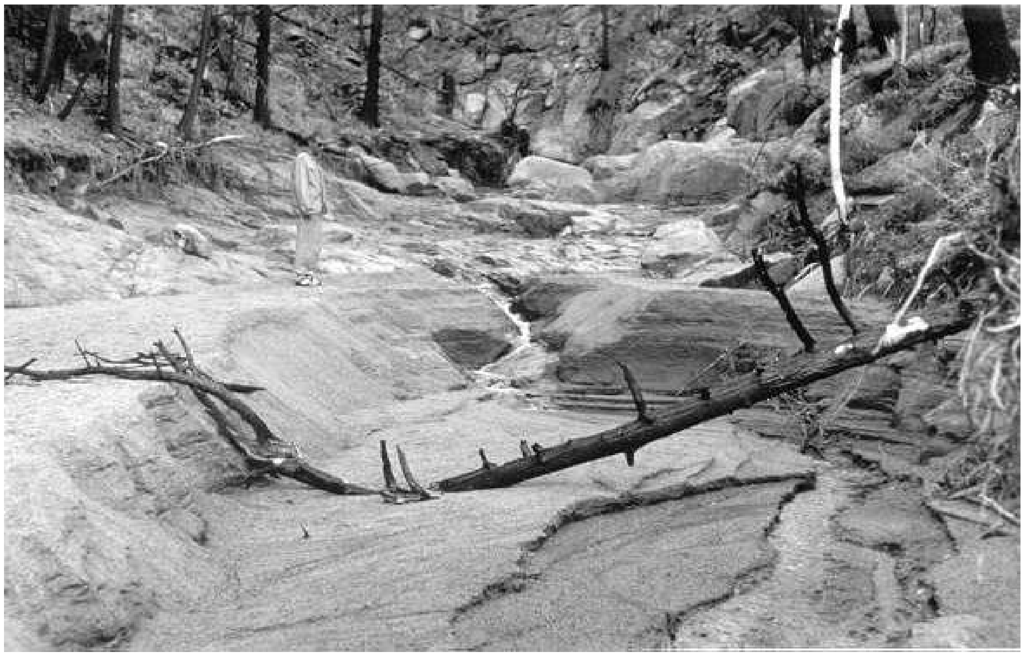


Figure 9. Views of Buffalo Creek during the summer of 1996, following the forest fire and subsequent floods. The upper photograph is looking upstream along a small tributary channel. In the foreground of the photograph, sediment is being alternately stired and then eroded and transported downstream from a former pool. Note the eroded banks at the rear of the photograph. The lower photograph is of an area of extensive sediment deposition, and damage to structures, along Buffalo Creek. The creek is at the far right in this photograph.

(4) Green River, Moffat County, Dinosaur National Monument: With the completion of Flaming Gorge Reservoir in 1962, flow along the Green River downstream from the dam changed dramatically. Prior to the dam, the spring flood would last for approximately a month, with an average discharge of 32,000 ft^3/s. The spring flood since the dam has averaged 4,000-4,700 ft^3/s. This reduction in peak discharge decreased the river's ability to transport the silt and sand abundantly supplied to the main channel by tributaries such as the Yampa River. The decrease in scouring of the channel bed and banks by floods also facilitated the invasion of the non-native riparian tree tamarisk, which grows in dense thickets that effectively trap sediment. As a result, portions of the Green River narrowed by 55% between 1871 and 1976. Fine sediment accumulation on spawning bars, along with the loss of floodplain nursery habitat and competition from introduced fish, has endangered the native species Colorado squawfish, razorback sucker, and humpback chub in the Green River.

(5) Arkansas River, Pueblo County: Water storage in Pueblo Reservoir has reduced the volume and velocity of flow along the Arkansas River downstream from the reservoir to the point that the channel is accumulating sediment. Citizens and city officials in La Junta believe that this accumulation of sediment in the channel, in combination

with the invasion of phreatophytic vegetation in the channel, has reduced flow conveyance, enhanced overbank flooding, and increased infiltration of water along the channel. As a result, the local water table has risen to the level that there are problems with saturation and salinization of agricultural fields, and flooding in residential basements.

Examples of hazards associated with the decrease of sediment

(1) Bessemer Ditch, Pueblo County: This irrigation ditch takes water out of Pueblo Reservoir on the Arkansas River. Prior to construction of the reservoir, the ditch had a 15-18% water loss to infiltration. This increased to 45% water loss following construction of the reservoir. The change in infiltration rate has been attributed to the absence of fine sediment in the flow along the ditch; previously, this fine sediment accumulated in the cracks that form periodically along the ditch, filling the cracks and reducing water loss. Approximately 10 miles of the 35-mile long ditch have been lined with cement, following a $1 million lawsuit that forced the government to line the ditch.

(2) Elkhead River, Moffat County: Elkhead Reservoir was constructed along the Elkhead River outside of Craig, Colorado in 1974. Landowners along the river have subsequently alleged that excessive erosion has occurred along this sand-bed meandering channel as a result of sediment retention in the reservoir. Approximately 4 miles of channel below the reservoir are affected, and in some areas the channel has migrated 70 feet laterally during the past 30 years.

Examples of hazards associated with contaminated sediments

(1) California Gulch, Arkansas River basin, Lake County: The former mining area of California Gulch has been designated as a Superfund site by the U.S. Environmental Protection Agency. Concentrations of heavy metals (Mn, Fe, Cu, Zn, Pb, Mb, Cd) in the Arkansas River downstream from California Gulch are highly dependent on flow and tend to increase during high spring runoff. This suggests that these metals are abundant in the fine sediments that have traveled from the tailings piles to the river, and are now carried downstream in suspension during high discharges. Much of the historic mining activity within the Arkansas River basin occurred along tributary streams. Today, the diversity and total abundance of aquatic insects are lower downstream from the junction of contaminated tributary streams, and higher below the junction of clean tributaries. The fish population is reduced or absent below the contaminated tributaries. Both insects and fish at polluted sites have higher concentrations of Zn, Cd, and Cu than those upstream.

(2) South Platte River, Adams, Weld, Morgan, Logan, Sedgwick Counties: The lower portion of the South Platte River basin in Colorado has been impacted by various human activities since the 1850s. Agricultural and urban land use in particular have produced contaminants carried into stream channels by surface runoff and subsurface flow. These contaminants are stored in river sediments for varying lengths of time, as well as being transported by stream flow and accumulating in the bodies of aquatic organisms.

The U.S. Geological Survey has made the lower South Platte River one of the target basins for the National Water Quality Assessment (NAWQA) Program. As of early 1998, NAWQA scientists had identified agricultural herbicides (atrazine, metolachlor, EPTC, cyanazine, DCPA, alachlor) and urban herbicides (prometon, simazine) and household insecticides (diazinon, carbaryl) in the South Platte River, as detailed on the NAWQA South Platte River home page on the Internet. Concentrations of these contaminants increase in summer and during stormwater runoff, but persist year-round.

In addition, approximately 7,000 tons of nitrogen and 860 tons of phosphorus enter streams in the basin each year, and phosphorus concentrations exceed the U.S. Environmental Protection Agency recommended limit for avoiding accelerated algae growth in lakes and reservoirs. Nutrient loads are highest downstream from Greeley, which has extensive feedlots.

The South Platte River has fewer species and numbers of fish near urban areas. Organochlorine compounds not used since 1972-1988 are still present, and at some sites these compounds occur at concentrations above levels of concern. The National Academy of Sciences guidelines for consumption of fish by wildlife are exceeded for DDT, PCB, and chlordane at some sites along the South Platte River. Further details of contamination along the South Platte River may be accessed at http://webserver.cr.usgs.gov/ nawqa/ splt/splt_home.html/.

(3) Upper Colorado River, Summit, Eagle, Garfield, Mesa, Delta, Montrose, and Ouray Counties: The upper Colorado River basin is another NAWQA study site. Bed sediments along several channels (e.g. French Gulch, Peru Creek, Cross Creek, Oh-be-joyful Creek, Snake River, Uncompahgre River) contain high levels of trace metals downstream from mining sites. Although the United States has not set standards for bed sediment contamination, the concentrations of zinc, cadmium, lead, copper, and arsenic in these sediments are at levels judged by Canadian standards to have adverse affects on aquatic biota. Fish at these contaminated sites are reduced in number or absent, and the fish have elevated levels of metals in their bodies. Although the metal concentrations in bed sediments drop quickly proceeding downstream from the mining sites, suspended sediments carry the contaminants much farther downstream.

(4) Terrace Reservoir, Alamosa River, Conejos County: Terrace Reservoir is 15 miles downstream from the Summitville Mine site, which has a history of underground and surface mining. The site has had increased surface mining since the early 1980s, which has resulted in increased sediment yield to the river and the reservoir. Sediments in the reservoir have levels of zinc, cadmium, lead, arsenic, copper, antimony, aluminum and iron that are elevated relative to background levels of these metals (elevated up to one thousand times background levels, in the case of copper). Fish kills have occurred in the reservoir, which is no longer fishable. The reservoir owners have also released sediments downstream into the Alamosa River.

OUR OPTIONS FOR MANAGING SEDIMENT AND WATER

Our abilities to mitigate the types of sediment hazards outlined in the preceding sections of this report are constrained by societal and legal considerations, environmental considerations, and technical considerations. Ultimately, mitigating sediment hazards will mean (1) keeping sediment out of sites where it creates a hazard, or removing the sediment once it reaches those sites; (2) supplying sediment to sites where its absence creates a hazard; or (3) containing contaminated sediment, or removing that sediment from sites where it creates a hazard. Water is critical to each of these mitigation methods because water is the most common agent of sediment transport, and the ratio of water/sediment will govern whether there is an excess or absence of sediment.

Societal and Legal Constraints

Both past and future trends in Colorado will constrain our ability to devise solutions that utilize water to mitigate sediment hazards. Colorado has an extremely complex history of water-law precedents, as well as the largest number of water lawyers per capita of any state. Because the system of prior appropriation, which serves as the ultimate basis for water allocation in Colorado, the ability to use water to supply or remove sediment from a site will be governed in many cases by the ratio of water costs to sediment-hazard costs. For over-appropriated rivers, the water necessary to reduce sediment hazards simply may not be available on a regular basis. At present, we do not have well-defined legal connections between water quality and water quantity.

Continuing trends of population growth in Colorado will also constrain our uses of water. The Front Range urban corridor of Ft. Collins to Pueblo presently has 3 million people; demographic projections predict 3.8 million people by the year 2020. However, the rapid growth of cities such as Durango and Steamboat Springs suggests that other regions of the state will also have increasing water demands. As demographic balance in the state continues to shift from agriculture toward urban and industrial consumption, both the pattern of water use and the cost of water will change.

The expectations of Colorado residents with respect to rivers are also changing. A predominantly urban population tends to place a high value on water-based recreation such as trout fishing, whitewater rafting, and reservoir fishing and boating. Individual groups of recreational users may prefer different patterns of water use (e.g. reservoir boating vs. whitewater rafting). Urban dwellers are also likely to have certain expectations with respect to rivers flowing through their communities; these channels should have clean, flowing water year round, but should not be subject to extreme floods or to lateral movement such as meander migration. In addition to the expectations of their constituents, local government agencies are subject to city, county, state, and federal regulations on flood control and urban drainage when designing water movement in urban environments.

A final legal constraint on water use is the State's legal obligations to other groups of water users. As one of the Upper Basin states in the 1922 Colorado River compact, the State of Colorado's use of that river's water is strictly confined. We also have other obligations to surrounding states such as Nebraska that are downstream along the South Platte River. Native American groups are arguing for water rights, as in the case of the Ute Mountain Ute Indian Tribe and the Animas-La Plata project, and federal land-management agencies are also legally requesting water rights related to the lands under their jurisdiction.

Sediment removal that is not water-based will be subject to legal constraints in the form of state and federal permitting procedures for dredging and filling operations.

Environmental Constraints

Legislation designed to protect environmental qualities, as well as public demands for environmental protection, will constrain some options for mitigating sediment hazards. Environmental legislation includes specific federal measures such as the Endangered Species Act, the Clean Water Act, and the Wild and Scenic Rivers Act. These Acts may regulate water, and hence sediment distribution.

Enforcement of measures such as the Endangered Species Act, for example, may involved specifying the instream flow necessary to maintain an endangered species. Federal regulations also govern activities in specially-designated public lands including the national parks, national forests, and wilderness lands administered by the Forest Service or the Bureau of Land Management. State regulations such as those governing Colorado's Clean Water Act, which includes narrative sediment regulations administered by the State Water Quality Control Commission with oversight by the U.S. EPA, pose additional potential constraints.

The enforcement of these various Acts by regulatory agencies may be limited by other legal constraints, such as prior appropriation or private property rights, because water quality is often related to water quantity. (The legal connection of water quantity and quality remains vague, however.) With increasing public demand for habitat preservation and outdoor recreation, it is no longer considered acceptable to mitigate sediment hazards to human structures at the expense of river ecosystems, as indicated by the public indignation following the deliberate release of sediment from Halligan Reservoir in 1996.

Technical Constraints

Our ability to mitigate sediment hazards is also constrained by our limited knowledge of the physical and chemical processes by which sediments and contaminants move through a river drainage basin. Both sediment yield from hillslopes and sediment movement in river channels are stochastic and unpredictable in that they are controlled by site-specific conditions that are difficult to characterize adequately enough for quantitative modeling and prediction. Numerous studies have demonstrated that timber harvest or agriculture within a drainage basin will increase sediment movement into river channels. But the existing sediment-routing models are not yet able to specify precisely that a 3% increase in cattle grazing within the basin, for example, will cause a 2% increase in sediment yield each year, which will in turn result in a 50% decrease in the useful life of a reservoir downstream.

Similarly, we can predict the average flow velocity at which a given size grain of sediment will begin to move in a stream, but that average value may have a high standard deviation

because if the sediment grain is sheltered by other larger particles the current will have to be much faster to move it than if the sediment grain is exposed on a flat channel bed. The uncertainty associated with this range of velocities may translate into a substantial uncertainty in the discharge necessary to flush sediment from a channel reach of concern.

Our ability to mitigate sediment hazards may also be constrained by difficulties in identifying the source of the hazard. We know relatively little of the "natural" or background levels of sediment present along some rivers in Colorado prior to 19th century human occupation of the river basins. This knowledge is particularly lacking for the eastern plains rivers. There is geological evidence of decades-long cycles of sediment accumulation and subsequent erosion along these rivers, independent of human land-use, and these cycles seem to be inherent to rivers in arid and semiarid regions of the western United States. Because of this inherent variability in sediment yield, it may be difficult to determine the specific cause of an increase or decrease in sediment along a river.

adsorbed onto particles of silt and clay and move only when the sediment moves. It is possible to test the effects of individual contaminants on a variety

We also know far too little about the behavior of contaminants in natural environments. Some substances move downstream in solution, others are of organisms in a lab setting, but it has been difficult to adequately reproduce the various combinations of contaminants to which an organism may be exposed in the real world. And it has proven difficult to predict chemical changes in contaminants once they enter the environment, such as the breakdown of DDT to DDE.

Legal, societal, environmental, and technical constraints pose numerous and complicated challenges for mitigating sediment hazards in Colorado as we enter the 21st century. Population growth in Colorado is unlikely to decrease in the immediate future, and individuals and groups of people are unlikely to stop pressing for the forms of natural resources management that they believe to be most appropriate. Within these constraints, there are some basic steps that may be taken toward mitigating present and future hazards resulting from sediments.

RECOMMENDATIONS FOR THE FUTURE

When addressing water and sediment issues in Colorado, we must begin by recognizing that we cannot restore the State's rivers to pre-19th century conditions, but we also cannot linearly extrapolate present patterns of water use without a serious degradation of the environment and our quality of life. The magnitude of the problem facing Colorado is suggested by the list of reservoirs within the State which are associated with some type of sediment hazard (Table 1). Americans have always struggled to find a balance between individual freedom and property rights versus the duty of the government to protect the rights and quality of life for the public as a whole. This is exemplified by past treatment of sediment issues in Colorado, where flow regulation or land use by private individuals or small companies may clash with governmental protection of clean water. Too often, decisions between these competing interests have been decided on a case-by-case basis, with legal precedents given equal or greater weight than scientific understanding of the physical processes involved. We begin, therefore, with two broadscale recommendations:

(1) Sediment hazard issues must be considered at the scale of the entire drainage basin, rather than on a very site-specific basis.

The loss of reservoir storage capacity may be a direct result of poor land-use and lang-management practices upstream from the reservoir, and the sediment release designed in an attempt to restore reservoir capacity may damage aquatic habitat downstream. The point is that the reservoir is not an isolated entity; it is closely connected to processes upstream and downstream. Therefore, any long-term plan to mitigate sediment hazards at the reservoir must also consider upstream and downstream controls. In addition, sediment generated at one point along a river may be carried miles downstream before it is deposited.

In practice, such an approach to hazard mitigation will probably require government oversight rather than piecemeal individual control. Although state government agencies have an abundance of work with existing regulations, it seems apparent that unless a knowledgeable, interdisciplinary oversight body is charged with the task of drainage-basin-scale management, problems will continue to be addressed within an inappropriately confined scope.

(2) The process of effective mitigation of sediment hazards would be facilitated by a decision-making process resting on scientific understanding of sediment dynamics rather than on legal precedents or court mandates.

For example, following the 1996 sediment release from Halligan Reservoir, a group of state government employees, private water users, environmental activists, and research scientists was formed to develop protocols for reservoir sediment release that would avoid the environmental degradation associated with the Halligan release. This is a less divisive and costly approach than a lawsuit to compensate parties adversely impacted by the sediment release. If analogous groups could develop protocols for minimizing the types of sediment hazards outlined in this report, everyone in Colorado would benefit greatly. The development of such protocols depends closely on widespread recognition and understanding of sediment issues. It seems unlikely, for example, that reservoir operators would deliberately destroy fish habitat or water quality if they were aware of other, less hazardous methods of managing sediment.

Table 1. A partial list of reservoirs in Colorado associated with some type of sediment hazard (Source: State Dept. Of Public Health and Environment, Water Quality Division, 305B Report, 1994). In addition to the reservoir problems listed here, the Colorado Department of Public Health and Environment's 1998 303(d) report (Water Quality Limited Segments Still Requiring TMDLs) lists 85 river segments with sediment problems, 12 river segments with metal-contaminated sediments, and 6 river segments with nutrient contamination.

RESERVOIRS	HAZARD
Cherry Creek	Contaminants - phosphorus
Chatfield	
Bear Creek	
Barr	
Jackson Lake	
Milton	
Prewitt	
Teller	Contaminants - toxics/metals
Mary	
Ladora	
Derby	
McPhee	
Navajo	
Narraguiunep	
Sanchez	
Terrace	
Pueblo	
Halligan	Excess sediment (perceived as a problem because of loss of storage within reservoir, or because reservoir releases too much sediment to river downstream)
DeWeese	
Strontia Springs	
Paonia	
Kenney	

At the more specific level, there remain several issues that must be addressed before we can effectively manage sediment. Each of these requires basic and applied research into sediment movement.

(3) Sediment accumulation in reservoirs

This is one of the most widespread sediment hazards in Colorado. We must improve our understanding of how to limit sediment movement into, and accumulation in, reservoirs.

Technologies exist for sediment dredging, bypassing, and flushing, but most of these are limited in application by cost or by downstream consequences such as possible water quality reduction from contaminants in the reservoir sediment.

(4) Sediment transport along channels

Whether the excess sediment comes from basin-wide land use, reservoir release, or flow diminution, sediment accumulation and consequent loss of water quality and habitat remain a problem along many rivers. We need to develop models that describe how various types and quantities of sediment are transported along different types of channels. Such models could specify, for example, the minimum flushing flow necessary to prevent downstream pool sedimentation during a reservoir sediment release.

(5) Contaminant dispersion and disposal

We are desperately in need of basic research on how individual contaminants combine with each other and with sediment along a stream channel; where they are stored and when they are mobilized; how they affect aquatic organisms and humans; and how long they remain biologically dangerous. We also need to develop basic protocols on how to remove contaminated sediments; how removal is accomplished; who pays for removal; and where the contaminated material is to be stored.

The hazards posed by sediment along rivers in Colorado are complex. Mitigation of these hazards requires a carefully planned and integrated approach which must include people with various backgrounds and areas of expertise. However, recognition of a problem is the first step toward solving that problem. We can continue to deal with each sediment hazard as it develops at a specific site. This approach is reactive and costly in that the situation is allowed to reach a hazardous level before action is taken, and that action is very limited in scope. Or, we can develop a proactive means of mitigating sediment hazards by designing basin-scale protocols for anticipating and preventing sediment-related hazards such as sediment releases from reservoirs or the downstream transport of contaminated sediments. As increasing population intensifies land use in Colorado, the potential for sediment-related hazards also increases. Now is the time to act.

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