MINING AND CHANNEL RESPONSE*

WILLIAM L. GRAF

ABSTRACT. Gold and silver mining activities in the Central City District, Colorado, caused severe disruption of the landscape. Central City is typical of mountain mining towns with clearly defined periods of discovery and settlement, bonanza, investment, development, and, finally, decline. Arroyos and gullies developed on many valley floors as responses to increases in channel tractive force from 1 dyne before settlement to 8 dynes during the mining period. The spatial distribution of energy and force has been substantially altered by human activities. Threshold values of erosive force were surpassed in response to changes in general basin vegetation cover, valley floor vegetation, channel slope, width, and roughness. Landscape stability, which depends on the relationship of the distribution of energy to the material landscape, has been reestablished in some basins in the Central City area. In other cases, several decades may be required before a balance between force and resistance is reached.

THE impact of resource exploitation on environmental systems has become a primary concern of American resource managers. The prediction of potential environmental impacts resulting from resource extraction is demanded by groups of citizens and government agencies, and it is required by law in many cases.[1] Modern demands for minerals and fossil fuels require increased extraction rates which, at the same time, increase the risk of environmental disruption.[2] This paper combines basic principles of physical processes with a historical, geomorphic investigation of mining in the Central City area of Colorado. The results of the historical approach provide an explanation of the present landscape and also provide insights into potential impacts of mining developments in other areas.

The investigation of change in fluvial geomorphic systems is made difficult by the lack of long-term data.[3] Some processes can be simulated in a restricted laboratory, some by numerical simulation, and some by intermediate scale physical models using sediment tanks.[4] In order to achieve manageable proportions, however, these approaches require dimensional and temporal simplifications that restrict their utility. Long-term (a century or more) recorded measurements of real geomorphic systems are the most desirable, but records are few and widely scattered. The development of a historical geomorphology for portions of the Central City Mining District is possible because

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[1] "Environmental Protection Agency, Preparation of Environmental Impact Statements," *Federal Register*, Vol. 40, No. 72 (April 14, 1975), pp. 16814–27.

[2] An early analysis of fluvial responses to mining in mountain areas is G. K. Gilbert, "Hydraulic Mining Debris in the Sierra Nevada," U.S. Geological Survey, *Professional Paper 105* (1917), 154 pp.

[3] J. B. Thornes and D. Brunsden, *Geomorphology and Time* (New York: John Wiley and Sons, 1977), p. 111.

[4] Restricted laboratory experiments frequently used in engineering and fluvial geomorphic research are typified by G. K. Gilbert, "The Transportation of Debris by Running Water," U.S. Geological Survey, *Professional Paper 86* (1914), 263 pp.; numerical simulations by R. F. Moore and J. B. Thornes, "LEAP—A Suite of FORTRAN IV Programs for Generating Erosion Potentials of Land Surfaces from Topographic Information," *Computers and Geosciences*, Vol. 2 (1976), pp. 493–99; and use of sediment tanks by S. A. Schumm and R. S. Parker, "Implications of Complex Response of Drainage Systems for Quaternary Alluvial Stratigraphy," *Nature*, Vol. 243 (1973), pp. 99–100.

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FIG. 1. Typical arroyo excavated in Lake Gulch. Abandoned buildings are at the level of the preincision surface.

of the extensive collections of photography of the area; prints are available from as early as 1864. Photogrammetric analysis of the historical ground photographs produced data on the dimensions of landforms during the period of human activity and environmental change. Field measurements in 1977 updated the record.

The major impact of mining on stream systems of the Central City Mining District was the initiation of stream entrenchment (Fig. 1). Many streams in the area developed arroyos in what apparently once were stable valley floors. The historical photographic evidence shows that stream entrenchment coincided with settlement, making climatic change an unlikely explanation of incisions. Mining activities, then, are directly related to explanations of the processes, forms, locations, and dynamics of arroyos.

NATURAL AND CULTURAL CONTEXTS

The Central City Mining District, located in Gilpin County, Colorado, is approximately 25 mi (40 km) northwest of Denver, in the Front Range Mountains.[5] The district includes about 25 mi^2 (75 km^2) of mountainous terrain that was riddled by mine shafts during the gold and silver rush of the 1860s (Fig. 2). Placer workings line some of the sinuous valley bottoms. The land surface ranges from 7400 ft (2250 m) to 10,000 ft (3050 m) in altitude, with rounded crests and steep but not precipitous hillsides. Valley bottoms are generally narrow and flat-floored. The montane climate is highly variable, depending on altitude. Rainfall varies from 50 in/yr (1270mm/yr) in the highlands to 20 in/yr (500 mm/yr) in the canyon bottoms. Mean monthly temperatures range from 22.5°F (−5.3°C) to 55°F (12.8°C).[6] The natural vegetation of the area was Canadian or Montane Zone Forest (aspen, spruce) at the higher altitudes and Transition Zone Forest (aspen, scrub oak, ponderosa pine) at the lower altitudes.[7] The complex geologic structure of the area includes highly con-

[5] The actual boundaries of the Mining District, an administrative unit for mineral accounting, have changed several times, but encompass most of the area shown (Fig. 1). For more precise information, see E. S. Bastin and J. M. Hill, "Economic Geology of Gilpin County and Adjacent Parts of Clear Creek and Boulder Counties, Colorado," U.S. Geological Survey, *Professional Paper 94* (1917), 379 pp., especially the plates.

[6] Bastin and Hill, op. cit., footnote 5, p. 8.

[7] H. Moenke, *Ecology of Colorado Mountains to Arizona Deserts* (Denver: Denver Museum of Natural History, 1971), pp. 28–42.

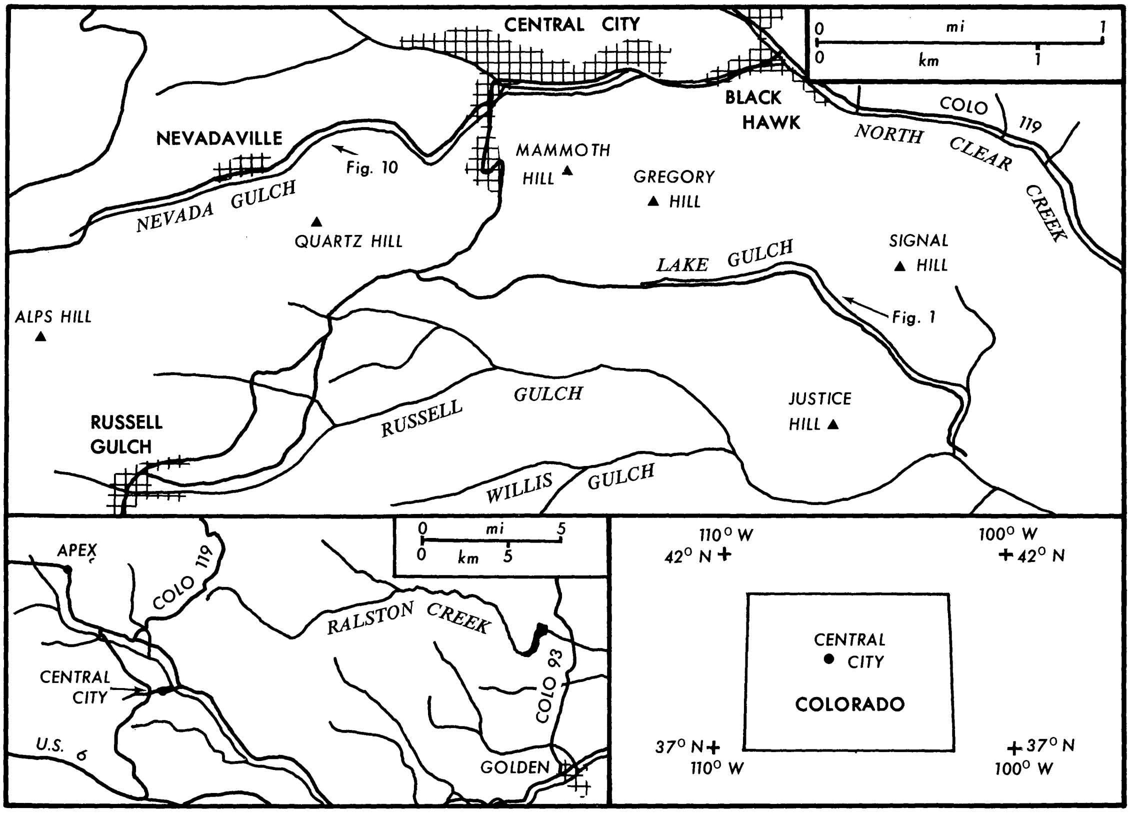

FIG. 2. Location and map of a portion of the Central City district.

torted Precambrian schists with quartz veins that carry the gold and silver. Granitic gneiss of Precambrian age is also common, with surficial deposits of Quaternary alluvium and colluvium in the valleys.[8]

Land utilization in the Central City district was typical of montane mining areas in the United States. Discovery of valuable minerals was followed by rapid development and settlement, investment and speculation, extensive construction, and then decline.[9] Changes in the natural landscape were closely related to changes in the cultural landscape. The spatial distribution of energy was also closely related to man's activities at the surface.

HUMAN HISTORY

In April, 1859, John H. Gregory discovered gold near what was to become Central City. Environmental disruption began immediately when aspen trees were cut to make claims

[8] J. D. Maher, "Detailed Sections of Pre-Pennsylvanian Rocks Along the Front Range of Colorado," U.S. Geological Survey, *Circular 68* (1951), 20 pp.; and T. S. Lovering and E. N. Goddard, "Geology and Ore Deposits of the Front Range, Colorado," U.S. Geological Survey, *Professional Paper 223* (1951), 319 pp.

[9] General reviews of the cultural, economic, and social aspects of western mining activities that had direct bearing on the environmental disruption are provided by W. S. Greever, *The Bonanza West: The Story of the Western Mining Rushes, 1848–1900* (Norman: University of Oklahoma Press, 1963); R. Paul, *Mining Frontiers of the Far West, 1848–1880* (New York: Holt, Rinehart, and Winston, 1963); and T. H. Watkins, *Gold and Silver in the West* (New York: Bonanza Books, 1971). The technology of mining in the montane regions is described by C. C. Spence, *Mining Engineers and the American West* (New Haven: Yale University Press, 1970); O. E. Young, Jr., *Western Mining: An Informal Account of Precious Metals Prospecting, Placering, Lode-Mining, and Milling on the American Frontier* (Norman: University of Oklahoma Press, 1970); and O. E. Young, Jr., with technical assistance of R. Lenon, *Black Powder and Hard Steel: Miners and Machines on the Old Western Frontier* (Norman: University of Oklahoma Press, 1976).

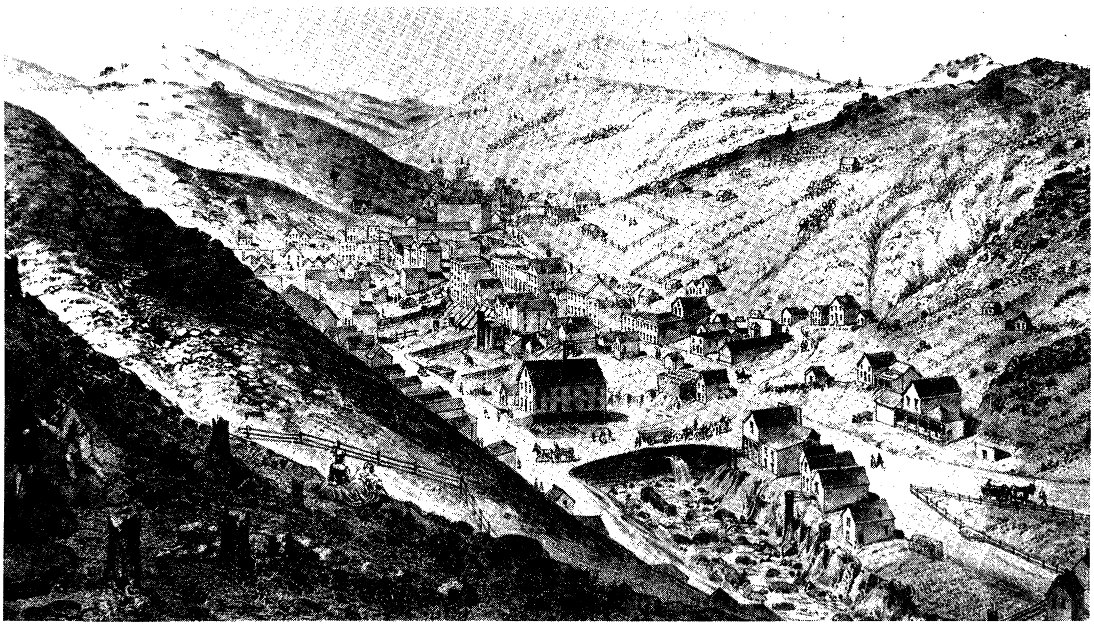

FIG. 3. A pencil sketch of Central City made about 1862, three years after the discovery of gold. Note the barren slopes, tree stumps in the lower left corner, and the radical incision of Gregory Creek below the stone bridge. (Photo #F7862, courtesy of the Western History Department, Denver Public Library.)

stakes.[10] The land was blanketed by Douglas fir, blue spruce, Engelmann spruce, and yellow pine. Early descriptions and pencil sketches show that the streams were not entrenched.[11] The announcement of the discovery of gold brought hordes of prospectors. By May there were 400 people working in the valleys; by June there were 6000; and before the end of July, there were 15,000. Drawings from the period 1859–62 show that, in the first few months, deforestation proceeded rapidly in response to the demand for lumber for sluice boxes, housing, and fuel. Many slopes were denuded within the first year of mining activity, although written accounts indicate some dense forest stands remained into 1860.[12]

During the bonanza period (1860–63) the remaining forests were cut as water projects and shaft mines. The booming towns consumed still more lumber. The timber was exhausted by 1863, and visitors noted the bald appearance of the landscape.[13] During the period of investment and speculation (1863–80), runoff from the surrounding slopes flooded the valley bottoms where the townsites were located. Flood damage was great and it constituted a major drain on municipal treasuries, an outcome dictated by building practices that permitted, for example, the construction of an opera house across a major stream.[14] Photographs and sketches from this period show that arroyo cutting occurred in the early 1860s (Fig. 3).

The decline of the Central City area began in 1878 with the depletion of easily worked deposits. By 1880, a substantial exodus of capi-

[10] C. Bancroft, *Gulch of Gold: A History of Central City, Colorado* (Boulder: Johnson Publishing Company, 1958), p. 32.

[11] Two of the best examples of early descriptions are those by H. Greeley, *An Overland Journey* (New York: Saxton and Barker, 1860); and A. D. Richardson, *Beyond the Mississippi* (New York: Bliss and Company, 1867). Reproductions of the pencil sketches are stored in the photographic collections of the Denver Public Library and the Colorado State Historical Society.

[12] Bancroft, op. cit., footnote 10, p. 71.

[13] E. Bliss, *A Brief History of the New Gold Regions of Colorado Territory Together with Hints and Suggestions to Intending Emigrants* (New York: John M. Amerman, 1864).

[14] The Opera House was built over Eureka Creek which ran through the basement of the building. C. Bancroft, *Silver Queen: The Fabulous Story of Baby Doe Tabor* (Denver: The Golden Press, 1953).

TABLE 1.—POPULATION OF GILPIN COUNTY, COLORADO

Year	Population
1860	15,000[1]
1870	5,490
1880	6,489
1890	5,867
1900	6,690
1910	4,101
1920	1,364[2]
1930	1,212
1940	1,625
1950	850
1960	685
1970	1,272

[1] Estimated population.
[2] Part of Jefferson County annexed by Gilpin County in 1913.
Population data taken from U.S. Census.

tal and workers was occurring as a result of mineral discoveries at Leadville, Colorado.[15] Thereafter, most towns were slowly depopulated and abandoned (Table 1). The Central City area declined steadily, except for a brief rejuvenation in the 1930s, until the tourist trade stimulated a modest recovery in the 1960s.[16] Reforestation has proceeded slowly without extensive replanting. Most modern forest development is taking place on cool, moist, north-facing slopes. Aspen (as a colonizing species) and ponderosa pine are becoming common, with some spruce. Some, but not all stream channels have become stable.

The response of geomorphic systems to deforestation and mining was twofold: erosion of slopes was accelerated and the stream channels became entrenched. Despite the rapid erosion of slopes, the sedimentary materials were meager in comparison with the amount artificially manipulated in the mining and construction efforts. Erosion by stream channels was a significant feature of historical geomorphology, however, and represents the most noticeable geomorphic effect of mining development aside from the numerous open shafts and tailings accumulations.

The stream-cut trenches are eroded up to 21 ft (7 m) deep into Quaternary valley fills that are silt-sand debris from nearby slopes. Coarse mining debris occurs in some channels. The trenches have nearly vertical walls and flat floors, with top width/mean depth ratios ranging from 1.5 to 10.0. Some might be best referred to as gullies and others as arroyos, but for the sake of simplicity, they all will be referred to below as arroyos (Fig. 4).[17]

PROCESSES

When the force of flowing water exceeds the resistance of materials, erosion results; when resistance is dominant no erosion occurs, and deposition may be observed. Although this simplification of a complex system ignores many factors, the tradeoff between force and resistance lies at the heart of explanation in geomorphology.[18] If the forces and resistances in the arroyo systems of the Central City district can be quantified, threshold values can be identified, along with environmental conditions associated with those thresholds.

The force exerted by flowing water on the bed of the channel can be measured as tractive force or as stream power per unit width. The present study uses tractive force because of its

[15] M. S. Wolle, *Stampede to Timberland*, second edition (Denver: Swallow, 1974).

[16] C. Bancroft, *Historic Central City* (Boulder: Johnson Publishing Company, 1964).

[17] Use of the terms gully and arroyo may be regionalized, with the Spanish derived term most common in the American Southwest. A convenient differentiation that would term trenches cut in colluvium as gullies and those cut in alluvium as arroyos does not appear in the literature. In the mining areas the valleys and sometimes the trenches cut into their floors were referred to as gulches.

[18] The first complete articulation of this point was by A. N. Strahler, "Dynamic Basis of Geomorphology," Geological Society of America, *Bulletin*, Vol. 63 (1952), pp. 923–38, but geomorphologists have been slow to develop the concept into applied physics and chemistry as indicated by W. H. Terjung, "Climatology for Geographers," *Annals*, Association of American Geographers, Vol. 66 (1976), pp. 199–222. Some examples of previous geomorphologic works that utilize measured force and resistance include: M. A. Carson and M. D. Kirkby, *Hillslope Form and Process* (Cambridge: Cambridge University Press, 1972), pp. 99–300; V. R. Baker, "Paleohydraulic Interpretation of Quaternary Alluvium Near Golden, Colorado," *Quaternary Research*, Vol. 4 (1974), pp. 94–112; P. W. Birkeland, "Mean Velocities and Boulder Transport During Tahoe-age Floods of the Truckee River, California-Nevada," Geological Society of America, *Bulletin*, Vol. 79 (1968), pp. 137–41; A. D. Knighton, "Stream Adjustment in a Small Rocky Mountain Basin," *Arctic and Alpine Research*, Vol. 8 (1976), pp. 197–212; P. D. Komar, "The Competence of Turbidity Current Flow," Geological Society of America, *Bulletin*, Vol. 81 (1970), pp. 1555–62; and A. D. Howard, "Effect of Slope on the Threshold of Motion and its Application to Orientation of Wind Ripples," Geological Society of America, *Bulletin*, Vol. 88 (1977), pp. 853–56.

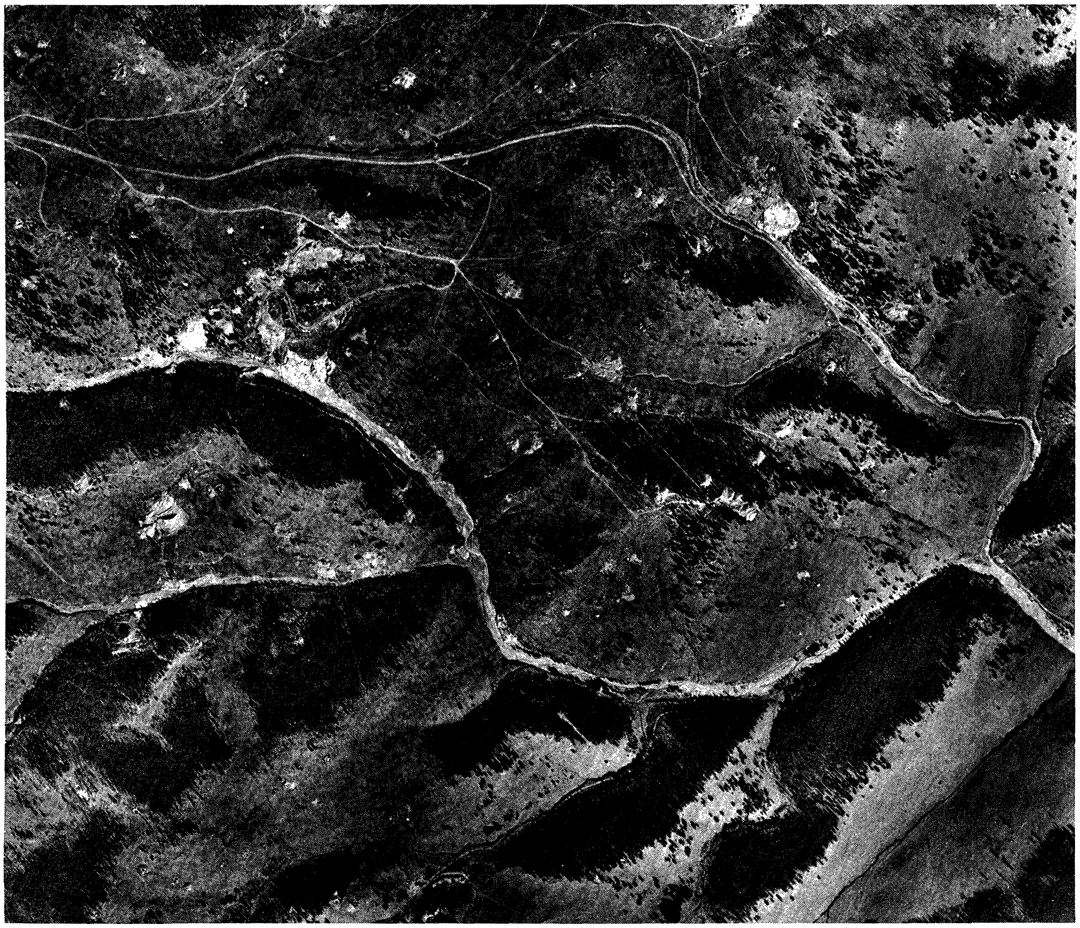

FIG. 4. Vertical aerial photograph of the Justice Hill area, Central City Mining District, showing channel incision, arroyo forms, and disruptions of mining activities (see Fig. 2 for location). North is toward the top of the image which represents an area 1.6 mi (2.6 km) by 1.4 mi (2.3 km). (Photo by the U.S. Forest Service, October 3, 1974, Photo #F16CN 08-047 2874 23.)

established utility in assessing erosive force. Values of tractive force may be converted to unit stream power by multiplication by velocity.[19]

Tractive force can be evaluated for a given cross section by use of a simple algorithm. Using the Cooke method, the algorithm begins by calculating the discharge for the 10-year flood at the cross section based on the characteristics of the basin above the site (Fig. 5).[20]

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[19] A complete discussion of the advantages and disadvantages of the employment of tractive force is provided by J. L. Bogari, *Sediment Transport in Alluvial Streams* (Budapest: Akademai Kaido, 1974), pp. 80–84. In the DuBoys equation R was assumed to be equal to 0.7 D because of the narrow, deep channels; see P. D. Wood, "Competence of Hope River, Jamaica, A Reappraisal of R as a Function of D," *Water Resources Research*, Vol. 13 (1977), pp. 1013–14. Unit stream power is discussed by C. T. Yang, "Unit Stream Power and Sediment Transport," American Society of Civil Engineers, *Journal of Hydraulics Division*, Vol. 98 (1972), pp. 1805–26.

[20] For a description of the Cooke method, see H. O. Ogrosky and V. Mockus, "Hydrology of Agricultural Lands," in V. T. Chow, ed., *Handbook of Applied Hydrology* (New York: McGraw-Hill Book Company, 1964), pp. 21–38 through 24–41. The Cooke method is a technique designed primarily for small agricultural watersheds where the drainage basin attributes of slope, drainage network, vegetative cover, and infiltration characteristics are combined to predict the coefficient and exponent of a power function relating discharge of the 10- or 50-year event to drainage area.

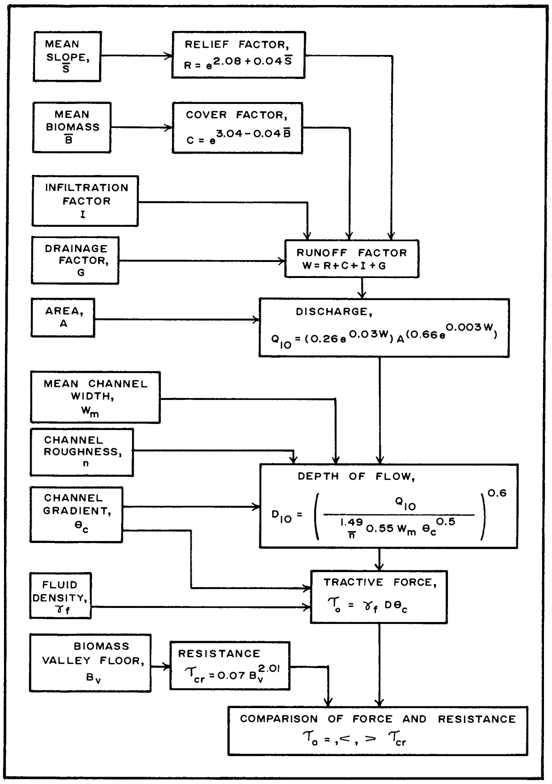


FIG. 5. Diagrammatic representation of the algorithm used to calculate force and resistance in channels. Cohesiveness of material is assumed constant, and therefore is not included in the analysis. Calculations are based on discharge events with a return interval of ten years. Symbols are defined in the boxes in which they first appear. Discharge and depth of flow are for the ten-year flood. Dimensions are as follows: biomass (kg/m^2), area (acres), Q_{10} (ft^3/sec), width (feet), fluid density (gm/cm^3), tractive force and resistance (dynes); all other variables dimensionless. Calculation is related to the Cooke method and is in English units because original publications and required inputs were in English units.

The discharge value is combined with the dimensions of the cross section to determine depth of flow by a modified form of the Manning equation. Finally, depth of flow is used to calculate tractive force by the DuBoys equation as a measure of erosive force.[21]

Resistance to erosive force is primarily a function of biomass on the valley floor. This resistance is embodied in the cohesiveness and weight of the materials and in the binding and protection afforded by vegetation. Cohesiveness is assumed to be a constant because all the Quaternary valley fills in the Central City district have approximately the same sedimentary characteristics and are relatively uniform throughout the valley systems. Vegetation on valley floors has been disrupted, however, and must be considered as a variable. Biomass on the valley floor at each cross section was estimated from average values for readily identified vegetation communities.[22]

Data from topographic maps describe the slope conditions of drainage basins (S), the nature of the drainage networks (G), and the drainage areas (A).[23] Biomass estimates were made from photographs. Published sources (checked in the field) provided descriptions of soil characteristics.[24] Field measurements of channel dimensions and slopes along with field estimates of channel roughness provided input for that part of the algorithm dealing with channel flow. Data from thirty-six sites within the Central City district and thirty-one sites in nearby, less disturbed areas provided information on a variety of combinations of the conditions.

If channel cross-section conditions are unchanging, the most significant variable affecting tractive force is vegetation (mean biomass) upstream from the site. Vegetation

The four basic attributes are assigned numerical values based on field observation and comparison with table descriptions that have assigned numbers. The relief factor and cover factor can be determined using quantitative variables as shown in the algorithm. The Cooke method is useful only for basins less than 10 mi² (16 km²) in area, and has been tested mainly on nonmountainous terrains. Its results are quite close to predictions made by models based strictly on empirical evidence for montane watersheds as reported by J. F. McCain and R. D. Jarrett, "Manual for Estimating Flood Characteristics of Natural Flow Streams in Colorado," Colorado Water Conservation Board, *Technical Manual 1* (1976).

[21] The Manning and DuBoys equations are discussed in a variety of contexts by Chow, op. cit., footnote 20.

[22] A review of mean biomass values is provided by R. H. Whittaker, *Communities and Ecosystems*, second edition (London: McMillan Press, 1975), p. 224.

[23] Each drainage basin yielded at least ten randomly located slope values, which were averaged to determine mean slope. The mean value was directly related to the relief factor by a function derived from tables and graphs published by Chow, op. cit., footnote 20. The drainage factor was assumed to be a value that reflected complete integration of the drainage system as defined by the same source.

[24] P. W. Schmidt and K. L. Pierce, "Mapping of Mountain Soils West of Denver, Colorado, for Land-use Planning," in D. R. Coates, *Geomorphology and Engineering* (East Stroudsburg, Pa.: Dowden, Hutchinson, and Ross, Inc., 1976), pp. 43–54.

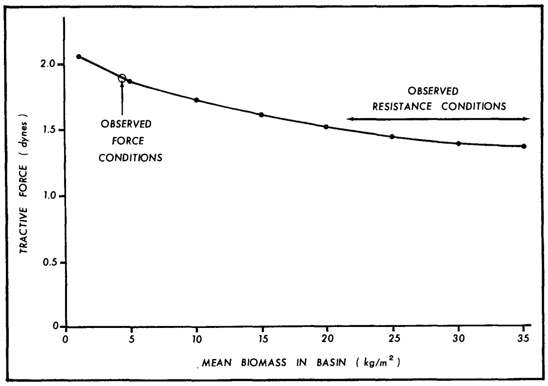


FIG. 6. The results of operating the algorithm under a variety of assumed vegetation covers in the basin of Nevada Gulch for discharge events with a return interval of ten years. Observed conditions used as inputs demonstrate that force exceeds resistance, explaining the extensive channel erosion found in the area.

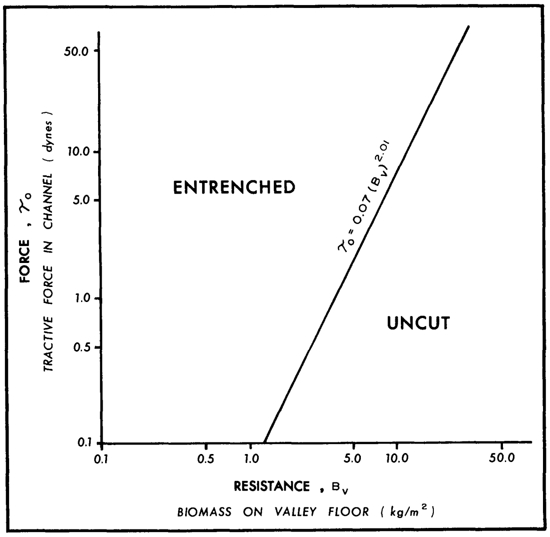


FIG. 7. The critical function relating resistance and biomass on the valley floor. Function derivation and additional data is given by Graf, op. cit., footnote 26. Only two of the sixty-seven sites do not fit the generalization of entrenched sites being limited to those plotting above and to the left of the line: in each case, the channel had been artificially manipulated. Force and resistance are defined in Fig. 5.

affects runoff and thus affects stream discharge, which, through an intermediate variable, depth of flow, affects tractive force. For Nevada Gulch the algorithm shows that tractive force under grassland conditions (biomass, 1-2 kg/m^2) is more than fifty percent greater than under heavily forested conditions (biomass, 30–50 kg/m^2). The 1977 conditions fall between these two extremes (Fig. 6).

Resistance to tractive force on the valley floors is related to vegetation cover near channel banks. If trees with extensive root systems accompanied by dense understory growth occur on the valley floor, then the force generated even by deep flows will be insufficient to cause channel incision. Shallow flows may initiate erosion, however, if only a sparse grass cover protects the valley floor (Fig. 7).[25] Channel cross section stability is thus determined by tractive force and the resistance generated by biomass at the site.

When force and resistance values are plotted on the same *x-y* coordinate system, the resulting plot field can be divided by a discriminant function that separates sites where erosion results from excess force from those without erosion because of excess resistance.[26] The function also specified the effective resistance by varying amounts of biomass on the valley floor. For example, if the vegetation at a valley floor site in the Central City area is shrubland with a biomass of 6 kg/m^2, stream entrenchment will occur if tractive force exceeds 2.5 dynes.

FORM

Accelerated channel erosion in the Central City area produced numerous arroyos with a variety of sizes. The arroyos are not stream channels but are trenches with channels at the bottom; calculated discharges for the ten- and fifty-year floods do not fill the trenches.

The cross sectional shapes of the trenches can be described systematically using allometric concepts.[27] Within each arroyo, and from one

[25] For an evaluation of the protective properties of vegetation along channels, see D. G. Smith, "Effect of Vegetation on Lateral Migration of Anastomosed Channels of a Glacier Meltwater River," Geological Society of America, *Bulletin*, Vol. 87 (1976), pp. 857–60; and R. C. Zimmerman, J. C. Goodlett, and G. H. Comer, "The Influence of Vegetation on Channel Form of Small Streams," *Symposium on River Morphology, International Association of Scientific Hydrology, Publication 75* (1967), pp. 255–75.

[26] For a more complete description of the evaluation of the constants of the discriminate function, see W. L. Graf, "The Development of Montane Arroyos and Gullies," *Earth Surface Processes*, Vol. 4 (1978), in press.

[27] For a useful discussion of allometric change in geomorphology see M. J. Woldenberg, "Open Systems —Allometric Growth," in R. W. Fairbridge, ed., *The*

TABLE 2.—SOLUTIONS OF THE FUNCTION $W = aD^b$

System	Number of observations	a	b	r^2
Southeast of Idaho Springs	18	3.39	1.09	0.78
West of Golden	6	4.59	0.78	0.72
Russell and Nevada	11	22.05	0.61	0.71
Lake and Virginia	9	1.27	1.29	0.62

arroyo to another, top width (W_t) and depth (D) vary at constant rates with the amount of material excavated, so that their rates of change are related to each other by a constant ratio, b:

$$dW_t/W_t\,dt = (dD/D\,dt)b.$$

The variables are related to each other by the integrated form:

$$W_t = aD^b.$$

In this application, changes in the variables result from change in location of the sample site. Presumably similar changes occur at the same site through time, though the rates of change may differ.

Allometry provides a convenient description of dimensional change, but explanation of the rates must appeal to basic geomorphic processes. Field observations indicate that arroyo width increases by mass movement processes; soil fall and slumping are common features. Arroyo depth increases because stream flow excavates poorly consolidated valley fills. In the spatial allometric applications (static allometry) or the temporal applications (dynamic allometry) there is no reason to assume a priori that these rates must be equal.[28]

Field measurements of top width and depth at sixty-seven arroyo cross sections show that the two dimensions do not change at the same rate. Least squares solutions of the logarithmic form of the power function given above yield b values with a wide range (Table 2). Except for the differences among the allometric rela-

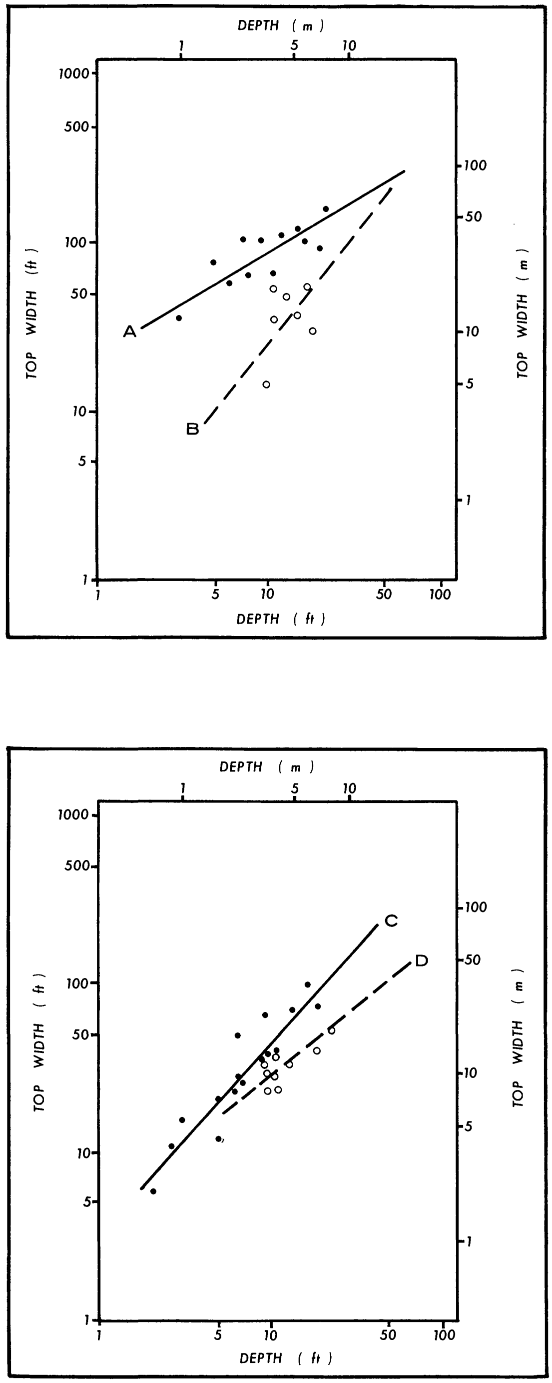


FIG. 8. The static allometric changes in arroyo width and depth for four areas: *A*, Russell and Nevada Gulches; *B*, Lake and Virginia Gulches; *C*, gulches southeast of Idaho Springs; *D*, gulches west of Golden. Some of the scatter of points may be accounted for by the variation in valley fill materials that were assumed to be constant for purposes of the present study. Age differences may also be important.

Encyclopedia of Geomorphology (New York: Reinhold Book Corporation, 1968), pp. 776–78; and W. B. Bull, "Allometric Change of Landforms," Geological Society of America, *Bulletin*, Vol. 86 (1975), pp. 1489–98.

[28] Static and dynamic allometry are defined and discussed for geomorphic applications by Bull, op. cit., footnote 27.

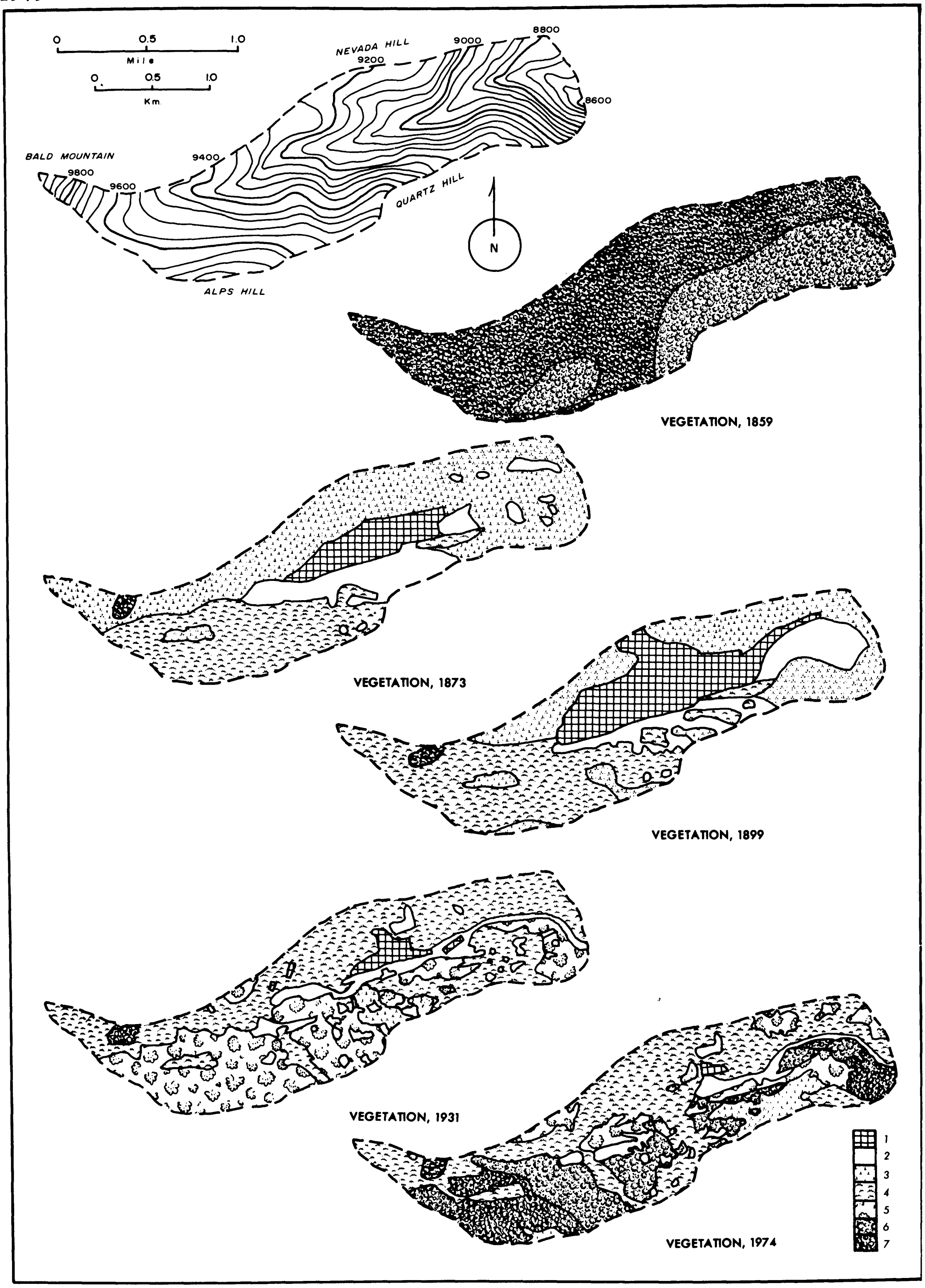
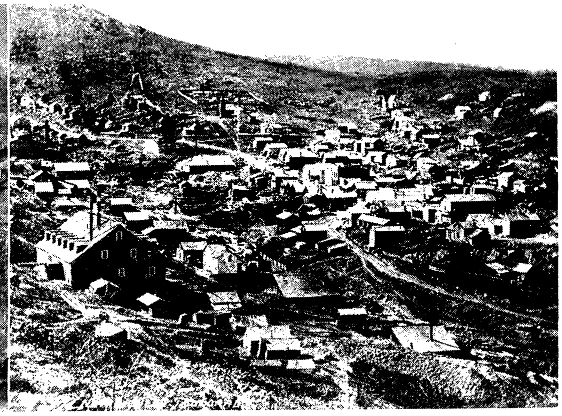


FIG. 9. Topographic map of the basin of Nevada Gulch from U.S. Geological Survey maps and vegetation history from the historical photography. Vegetation key: 1) artificial surfaces without vegetation; 2) barren ground; 3) short grass; 4) mixed grasses and low shrubs; 5) shrubland; 6) mixed forest, predominantly deciduous trees with some conifers; 7) coniferous forest.

1864



1873

1879

1898

FIG. 10. More than a century of cultural and geomorphic change is shown in this series of photos of Nevadaville. All the views were taken from approximately the same camera station, shown on Fig. 2. All photos except the 1977 view are from copies in the Western History Department, Denver Public Library, all rights reserved. 1864, photographer unknown, no number. 1873, photo by Reed and McKenney, #M131. 1879, photo by L. McLean, #F5860. 1898, photographer unknown, #F10102. 1899, photo by H. H. Lake, no number. 1905, right image of a stereo pair, photo by A. E. Dickerson, no number. 1931, photographer unknown, no number. 1977, photo by author.

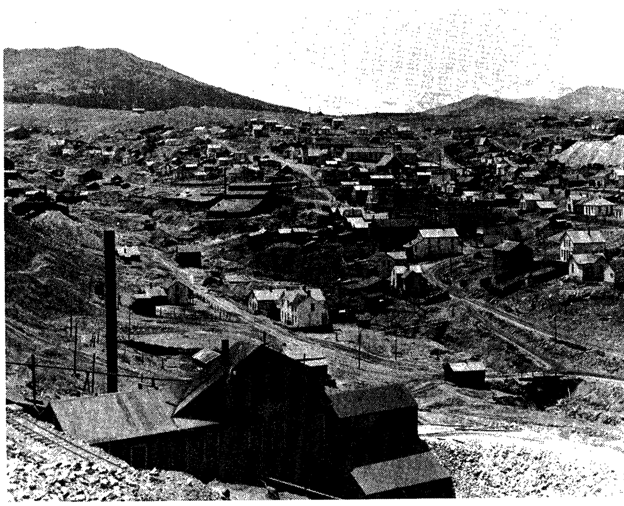
tionships, there do not appear to be other systematic variations among the groups of arroyos (Fig. 8). Perhaps a variety of ages and subtle differences in bank materials explain the variation in allometric relationships.

The ultimate dimensions of developing arroyos may be determined approximately by the allometric models. Calibration of the models to areas other than the montane valleys of the Front Range probably would reveal different constants for different materials, landscapes, and climatic conditions.

DYNAMICS—GEOMORPHIC HISTORY

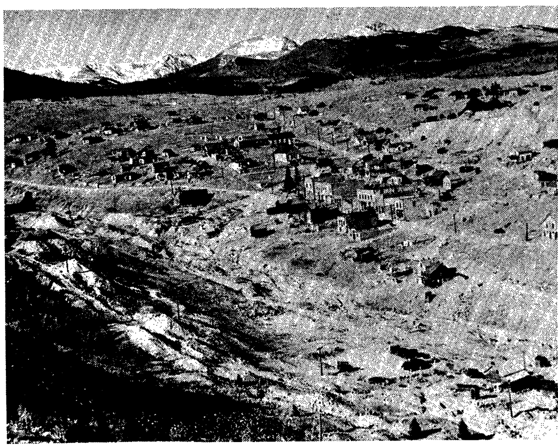
The mining areas in and near Central City were photographed several times between 1864 and the present. The glass plates, negatives, and prints provide an unbiased source of information about environmental conditions. Many of the photographs were taken from high vantage points, thus permitting vegetation mapping for times past.[29]

[29] Major storage sites for the surviving historical photography of the Central City area include the

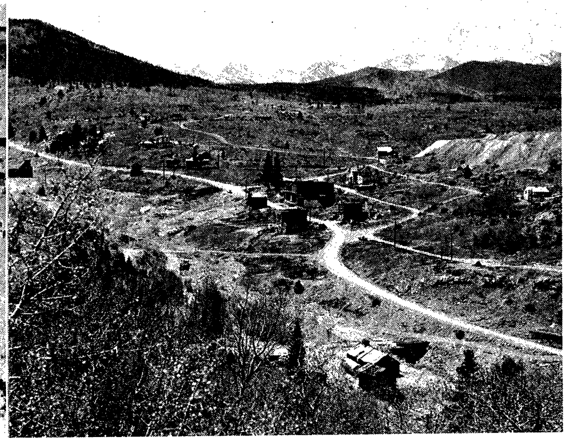


1899

1905



1931



1977

Photogrammetric methods originally designed for use with oblique aerial photographs are also useful for mensuration of oblique photographs taken from ground stations.[30] Because the optical characteristics of the ground cameras are unknown, the location of each camera station and the true dimensions of some object in each image must be known in order to derive useful measurements. In many cases, analysis of prints from glass plates is easier than use of modern 35mm images because the glass plates produce large, sharply defined images. Comparison of photo-derived measures with actual field measurement of the same dimensions showed that errors normally do not exceed five percent, except where the camera station could not be accurately located or when the negative was excessively grainy. Poor quality photographs were not used for dimen-

Western History Department of the Denver Public Library, the photo collection of the Colorado State Historical Society, the Colorado State Archives, and the Photo Library of the U.S. Geological Survey, all in Denver.

30 The utility of imagery from nonmetric cameras in determining distances and dimensions is discussed by I. W. Faid, "Photogrammetric Potentials of Nonmetric Cameras," *Photogrammetric Engineering and Remote Sensing*, Vol. 42 (1976), pp. 47–49. Oblique metrics are outlined in detail by the American Society of Photogrammetry, *Manual of Photogrammetry* (Falls Church, Va.: American Society of Photogrammetry, 1960), pp. 25–48, 875–918.

sional analysis. Almost all areas of the Central City district are covered by some historical photography. The most complete and useful collection is for the Nevadaville area and Nevada Gulch.[31]

Early written accounts indicate that the drainage basin of Nevada Gulch above Central City was completely forested in 1859 (just before the gold and silver rush), but by 1873 all the forests had been cut. The basin was converted to grass cover except for those parts occupied by the town or by mine tailings. The drastic alteration in vegetation cover explains the numerous flash floods experienced in subsequent years by the downstream towns of Central City and Black Hawk.[32] Reforestation had not yet begun by the turn of the century, and large areas of barren and artificial surfaces increased the flood problem. Human use of the basin decreased rapidly after 1900. Reforestation is apparent in some photos by 1931. Vegetation in the 1970s is mixed conifers and grasses. Barren spots mark former mining activities. Except for a few buildings, the town site is not a physically significant part of the drainage area (Fig. 9).[33]

Eight photographs, all taken from approximately the same camera station, show the geomorphic adjustments of the stream in Nevada Gulch to changes in tractive force from 1864 to 1977 (Fig. 10). All the photos show a crossing of Nevada Gulch where a bridge was eventually installed.

Before the discovery of gold and silver, tractive force in Nevada Gulch was well below the threshold value required for entrenchment. The resistance threshold decreased when the valley floor was cleared in 1860. Tractive force increased, insuring erosion (Fig. 11). In the 1870s, developments on the floor constricted stream flow and further increased tractive force. Reforestation of the basin brought about a gradual decline in tractive force in the channel, but the bridge abutments continue to restrict

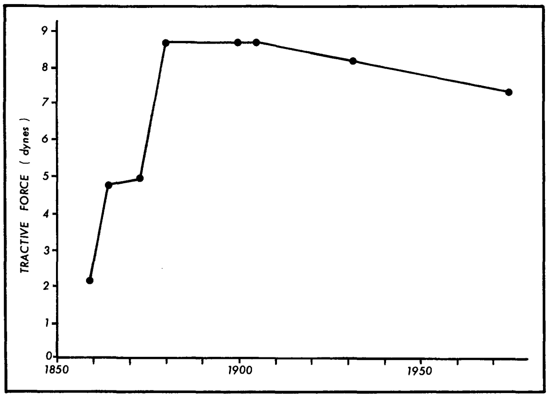


FIG. 11. Calculated levels of tractive force for discharge events with a return interval of ten years.

the flow and keep levels of tractive force high in comparison with original undisturbed values.

Stability, in the form of resistance exceeding force, will return to the Nevada Gulch channel only after further reduction of runoff by reforestation, increased resistance on the barren valley floor, and the removal of constricting structures along the stream. Other basins without structures such as bridge abutments have already ceased downcutting. Ponderosa and white pine trees growing on the floor of Lake Gulch provide dendrochronologic evidence for the stability of that feature since the 1930s. Some arroyo floors in other nearby basins were also stabilized in the 1930s. The widespread stabilization of arroyo floors at about the same time may simply be caused by similar dates of disruption followed by similar rates of adjustment to a new stable condition.[34] Many arroyo floors, especially in the mining area, are still unstable and probably will remain so for some time.

CONCLUSIONS

Increased mining pressure on montane areas of the American West is a logical outcome of the demand for minerals and fuels. Mining activities produce environmental costs in the form of disruption and destabilization. Valley floors and stream systems are especially vulnerable. Analysis of the Central City Mining District shows that consideration of the material landscape is insufficient to explain and

[31] The Western History Collection of the Denver Public Library has an extensive collection of photos of the Nevadaville area, which the Colorado State Historical Society's photo collection supplements.

[32] Black Hawk was especially hard hit with a major flood in 1895 which finally lead to investment in engineering structures; R. L. Brown, *Colorado Ghost Towns—Past and Present* (Caldwell, Idaho: Claxton Printers, Ltd., 1973), pp. 45–51.

[33] This general history has been deduced from the photographic evidence.

[34] Regional similarity in rates of change in gully development has been noted in the Denver Basin; W. L. Graf, "The Rate Law in Fluvial Geomorphology," *American Journal of Science*, Vol. 277 (1977), pp. 178–91.

manage the disruption; adjustments in the distribution of energy and force also must be understood.

Thresholds of resistance to erosion along montane streams depend on several factors, only one of which (vegetation) was examined in this study. Force levels, on the other hand, may exceed thresholds of resistance as a result of changes in discharge, channel slope, channel width, or roughness, all subject to human intervention. Control of structure locations and the management of vegetation distribution throughout the drainage basins, especially on valley floors, are critical to the control of force levels in streams of the Central City area.

Tractive force of the 10-year flood in stream channels in the Central City area increased from less than 1 dyne before settlement to more than 8 dynes after severe disruption. Force exceeded resistance by a wide margin, resulting in arroyo development. Arroyo dimensions can be described using allometric principles, with width and depth changing at different rates. The distribution of arroyos is erratic and depends solely on the local relationship between force and resistance.

Montane stream channels in the Central City area responded to mining and lumbering activities within a few months of the initial disruptions in 1859. Channels became entrenched and, while some arroyos stabilized sixty to seventy years after their inception, arroyos with restricted channel widths remain unstable more than a century later. Vegetation management appears to be the most significant factor in assessing the impact of human activities on the relationship between force and resistance in montane streams.