GEOMORPHIC EVALUATION OF EROSIONAL STABILITY AT RECLAIMED SURFACE MINES IN NORTHWESTERN COLORADO

By John G. Elliott

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GLOSSARY

aggradation.--The process of building up a surface by deposition; used in this report to indicate net deposition of sediment in a stream channel.

degradation.--The process of lowering a surface by erosion; used in this report to indicate net erosion of sediment from the bed of a stream channel or gully.

drainage basin.--A part of the land surface that is occupied by a drainage network, consisting of stream channels and all areas that contribute runoff to the streams.

drainage network.--A system of stream channels consisting of a principal stream and its tributaries.

geomorphology.--The science encompassing the form of the Earth's surface, and the processes that are active in changing it.

gradient.--The degree of inclination of a land surface, expressed in feet per feet.

gully.--An erosion channel or small ravine "so deep that it cannot be crossed by a wheeled vehicle or eliminated by plowing" (American Geological Institute, 1987, p. 295).

hillslope.--An inclined land surface below a drainage-basin divide or interfluve where much surface runoff originates; often grades into a valley floor.

hollow.--A topographic depression; a part of a hillslope having concave contour lines in plan view; a moisture-collecting area, occasionally supplying a discontinuous gully or stream channel with runoff.

hypsometric curve.--The graphical representation of the distribution of land mass in a drainage basin; provides information about erosional history and sediment production (Schumm, 1956).

pedology.--The science encompassing the origin and character of soils.

premine.--The condition of the land surface before disturbance by surface mining.

reach.--An extended part or segment of a stream channel or valley.

reclaimed.--The condition of the land surface after disturbance by surface mining and reclamation, including spoil regrading, topsoil replacement, and seeding.

rill.--A small erosion channel, often linear and discontinuous.

stable.--The condition of a valley floor or stream channel in which, over some period of time (years to tens of years), there is no progressive degradation, no progressive aggradation, nor widespread lateral erosion.
stream channel.--The geomorphic feature occupied by a stream, consisting of the bed and banks; may be dry, or filled partly or entirely by flowing water; may be naturally formed or manmade.
threshold.--A set of geomorphic conditions at which the land surface or a stream channel is incipiently unstable; when a threshold is exceeded, the surface may undergo rapid change.
unmined.--The condition of the land surface that has not been disturbed by surface mining.
unstable.--The condition of a valley floor or stream channel in which, over some period of time (years to tens of years), there is progressive degradation, progressive aggradation, or widespread lateral erosion.
valley floor.--A topographic depression or hollow in which surface and ground water collects and often forms a stream channel; laterally bounded by hillslopes.

LIST OF SYMBOLS

AD_r = Active rill density
A_d = Drainage basin area (acre)
AGI = Area-gradient index (acre)
A/T = Ratio of active- to total-rill densities
c, c', j, k, rf = Coefficients
D = Flow depth (foot)
D_d = Drainage density (foot per acre)
g = Gravitational acceleration
G_{25} = Hillslope gradient at 25 percent of total hillslope length (foot per foot)
G_{50} = Hillslope gradient at 50 percent of total hillslope length (foot per foot)
G_{75} = Hillslope gradient at 75 percent of total hillslope length (foot per foot)
G_{max} = Maximum hillslope gradient (foot per foot)
G_s = Hillslope gradient at a point (foot per foot)
G_v = Valley gradient (foot per foot)
HD_r = Healing-rill density
L_c = Total stream-channel length (foot)
L_s = Hillslope length (foot)
LG = Hillslope-length, hillslope-gradient product (foot)
n = Sample size
Q = Discharge (cubic foot per second)
R = Hydraulic radius of flow
R^2 = Coefficient of determination
R_a^2 = Coefficient of determination, adjusted for degrees of freedom

r = Coefficient of correlation
S = Energy slope, or stream-channel gradient (foot per foot)
TD_r = Total-rill density
VEI = Valley-erosion index
VEI_t = Threshold value of the valley-erosion index, 1.0
W = Flow width (foot)
W_v = Valley-floor width (foot)
Y = Age of hillslope since reclamation (year)
γ = Unit weight of water, 1.0
Ω = Total stream power
Ω_i = Geomorphic index of potential total stream power
ω = Unit stream power
ω_i = Geomorphic index of potential unit stream power
ρ = Fluid mass density
τ_o = Average shear stress
τ_i = Shear-stress indicator

CONVERSION FACTORS AND RELATED TERMS

Multiply inch-pound unit	*By*	*To obtain metric unit*
acre	0.4047	hectare
acre per foot (acre/ft)	1.3277	hectare per meter
foot (ft)	0.3048	meter
foot per acre (ft/acre)	0.7532	meter per hectare
foot per foot (ft/ft)	1.00	meter per meter
foot per 100 square feet ($ft/100\ ft^2$)	3.281	meter per 100 square meters
inch (in.)	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
square foot	0.09290	square meter

The following terms and abbreviations also are used in this report.

gram per cubic centimeter (g/cm^3)
millimeter (mm)
millimeter per minute (mm/min)

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ABSTRACT

Recurrent rill and gully erosion have been observed on some reclaimed surface-mined land in northwestern Colorado. Surface coal mining and reclamation activities have resulted in substantial changes in geology, geomorphology, pedology, vegetation, and hydrology; accelerated erosion of some reclaimed lands may be a result of these changes. Rill erosion and gully erosion of hillslopes and valley floors were studied at the Trapper, Hayden Gulch, Grassy Gap, Seneca II, CYCC, and Edna Mines in Moffat and Routt Counties. Data were collected from reclaimed and nearby unmined areas.

Reclaimed and unmined hillslopes were similar geographically; however, reclaimed hillslopes had greater topsoil bulk densities, lower topsoil-infiltration rates, less woody vegetation, and a greater occurrence of rill erosion. Most reclaimed hillslopes had straight or convex hillslope profiles, whereas most unmined hillslopes had complex profiles. Rills on reclaimed hillslopes generally have developed on the mid-hillslope to lower hillslope segments, on segments of steep gradient, or on segments below recent surface disturbances. Total-rill density was positively correlated with the product of hillslope length and hillslope gradient and inversely correlated with age since reclamation. Gullies on some reclaimed hillslopes developed on steep or convex hillslope segments and below subtle topographic depressions that may have functioned as moisture-collection areas.

Valleys in reclaimed drainage basins were re-created by spoil-material handling and lacked resistant geologic controls. Reclaimed valleys often were narrow or v-shaped in cross section. Most stable reclaimed valley floors could be distinguished from unstable reclaimed valley floors on the basis of three geomorphic variables; drainage area, valley gradient, and valley-floor width. The area-gradient index, the product of drainage area and valley gradient, is a geomorphic index of the potential total stream power acting on a valley-floor reach. The relation between valley-floor width and area-gradient index and the clustering of data from stable and unstable valley-floor reaches defined the valley-erosion threshold. Reclaimed valley floors that had valley-floor width less than the valley-erosion threshold were more likely to be gullied than reclaimed reaches that had valley-floor width greater than the valley-erosion threshold. Valley-erosion indices that quantified the relative stability or instability of reclaimed valley-floor reaches were calculated with reach-specific geomorphic data and the coefficient and exponents of the valley-erosion threshold. Empirically derived geomorphic relations may be useful as planning tools in future reclamation projects or in mitigating existing erosional instability.

INTRODUCTION

Reclaimed surface coal mines in northwestern Colorado have great potential for accelerated erosion of topsoil and spoil materials. Surface mining and reclamation often result in substantial changes in geology, geomorphology, pedology, vegetation, and hydrology. Rills and gullies may develop on reclaimed land surfaces where erosive forces exceed resisting forces. Rill and gully erosion commonly are attributable to immature or deficient vegetation cover, high rates of runoff, and erodible materials. Recurrent rill and gully erosion in reclaimed areas where vegetation cover has been reestablished may be caused or exacerbated by the geomorphic condition of the reclaimed land surface.

The Surface Mining Control and Reclamation Act, Public Law 95-87 (SMCRA), was enacted in 1977. The Act and the regulations promulgated in accordance with the Act provide design and performance standards for many aspects of coal mining, including postmining topographic configuration, structural stability, and sediment production of reclaimed surface-mined lands. However, the design and construction of an erosionally stable, reclaimed land surface, which complies with all the applicable design and performance standards, can be a formidable task.

Reclamation of surface-mined lands may be most effective if reclamation planners have a better understanding of factors that contribute to erosion. When the dominant geomorphic forms and processes that affect erosion on reclaimed surface-mined lands are identified, reclamation plans can be developed that decrease future erosion potential, and appropriate actions can be initiated to mitigate existing erosion problems. Therefore, to identify and attempt to improve the understanding of the factors contributing to erosion, the U.S. Geological Survey began a cooperative study with the Colorado Mined Land Reclamation Division in 1985 to investigate recurrent erosion of reclaimed surface coal mines in northwestern Colorado.

Purpose and Scope

This report identifies geomorphic, pedologic, vegetation, and hydrologic conditions that are associated with erosion of reclaimed surface-mined lands in northwestern Colorado. The report also presents methods for determining the appropriate values of geomorphic variables that can be manipulated during reclamation to increase erosional stability. A section on geomorphic principles associated with erosion of reclaimed land surfaces is designed for use as a primer by mine personnel and reclamation planners.

Although the potential exists for accelerated rill erosion and gully erosion on all land surfaces, this study was limited to reclaimed surface coal mines and nearby unmined areas in northwestern Colorado. Data were collected at the Trapper, Hayden Gulch, Grassy Gap, Seneca II, CYCC, and Edna Mines in Moffat and Routt Counties. The areas of interest in this study were those that were reclaimed under jurisdiction of current (1988) SMCRA reclamation regulations, yet were still affected by relatively rapid erosion rates several years after reclamation activities were completed.

Geomorphic, pedologic, vegetation, and hydrologic data were collected onsite and from topographic maps. Data from reclaimed areas undergoing accelerated erosion were compared with data from reclaimed areas undergoing minimal erosion to identify conditions that controlled erosion on reclaimed surface-mined lands and to identify some postmining equilibrium landform characteristics. These data also were used to develop threshold relations.

Background

Erosion at reclaimed surface coal mines is most obvious immediately following spoil regrading and topsoil reapplication when vegetation cover is absent or immature. The rate of erosion decreases rapidly as vegetation cover increases during the first few years after reclamation. However, erosion rates remain high in some areas even after vegetation has become established because other factors, such as steep hillslope gradients or narrow valley floors, decrease erosional stability.

Two important types of erosion were observed at reclaimed surface coal mines in northwestern Colorado: (1) Rills that eroded topsoil, and (2) gullies or unstable stream channels that eroded topsoil and spoil material. Sheet erosion of topsoil was observed in areas of sparse vegetation cover, but this type of erosion may not be a major source of topsoil loss in reclaimed drainage basins. Mass movement of topsoil and spoil material also was observed at some reclaimed surface coal mines. Although mass movement can disrupt large areas of land, it was not included in this study.

Rills are small (generally less than 1 ft wide and 1 ft deep), commonly parallel and discontinuous, erosion features that sometimes develop where surface runoff has become channelized. Rills entrain and redistribute topsoil and impede vegetation growth on reclaimed land surfaces. Gullies are larger, unstable channels or ravines that are a source of sediment in a drainage basin and a conduit for sediment transport out of a drainage basin. Gullies may be discontinuous or continuous, have large longitudinal extent, and be integrated with other tributaries. Most gullies on reclaimed surface coal mines in northwestern Colorado are incised through the topsoil zone (about 0.8 to 1.5 ft thick) into the underlying spoil material.

Erosion at reclaimed surface coal mines was associated with two distinct geomorphic areas: (1) Rills, and occasionally gullies, were observed on hillslopes; and (2) gullies, or unstable stream channels, were observed on valley floors. Hillslopes are the inclined land surfaces below drainage-basin divides or interfluves where substantial runoff originates. Lower parts of many hillslopes grade into valley floors. Valley floors are topographic depressions in which surface and ground water collect and often form stream channels. Hillslopes and valley floors are geomorphically distinct, but integrated components of a drainage basin; however, these geomorphic areas were studied independently because different processes are active in each.

Approach

Reclaimed hillslopes and valley floors that exemplified a variety of geographic conditions typical of surface coal mines in northwestern Colorado were selected for study. However, to minimize the effect of immature vegetation cover, data were collected only from sites that had been reclaimed for a minimum of 3 years. Selection of study sites was stratified to ensure that a variety of conditions was included in the data set. Although random selection of study sites might have produced a large data set representing proportionally the conditions at the mines, random sampling would have been prohibitively expensive and time consuming. Within each study site (a hill-slope or a valley-floor reach), data were collected systematically at regular intervals.

Data from unmined hillslopes and valley floors also were collected and compared to data from the reclaimed hillslopes and valley floors. Although unmined lands are substantially different from reclaimed surface-mined lands in geologic materials, topsoil development, vegetation succession, and other characteristics, a comparison of two types of land indicates how conditions that control erosion on reclaimed surface-mined lands differ from conditions that control erosion on unmined lands.

A valley-erosion threshold equation for reclaimed drainage basins was empirically derived using geomorphic data collected at stable and unstable sites. The geomorphic variables in the equation can be manipulated to some degree during reclamation. Geomorphic equations, such as the valley-erosion threshold, may be used by mine companies and regulatory agencies to determine appropriate values of some geomorphic variables and to design self-sustaining landforms that have a minimum erosion potential.

Description of Study Area

Several surface coal mines are located in the Williams Fork Mountains in Moffat and Routt Counties. Large areas, including entire drainage basins, have been mined and reclaimed since SMCRA became effective. Many hillslopes and valley floors have been reclaimed in recent years under jurisdiction of the current (1988) SMCRA reclamation regulations, but accelerated rill and gully erosion continues in some areas. The study area includes the Trapper, Hayden Gulch, Grassy Gap, Seneca II, CYCC, and Edna Mines (fig. 1).

The Williams Fork Mountains trend east-west and primarily are composed of uplifted and folded sedimentary formations of Cretaceous age. The Williams Fork Formation and the Iles Formation contain the coal beds being mined in this area. Elevations in the study area range from about 6,300 ft near Hayden to more than 8,300 ft along the crest of the Williams Fork Mountains. Mean annual precipitation in the Williams Fork region varies with elevation and ranges from about 19 to 25 in/yr (Colorado Climate Center, 1984). Much of the precipitation occurs as snow. Many first- and second-order streams in unmined drainage basins in the study area are intermittent. Snowmelt is the predominant runoff-producing process, although occasionally thunderstorms produce runoff. Native vegetation communities in the study area include grassland and big sagebrush at lower, drier elevations, and mountain shrub and aspen at higher, wetter elevations.

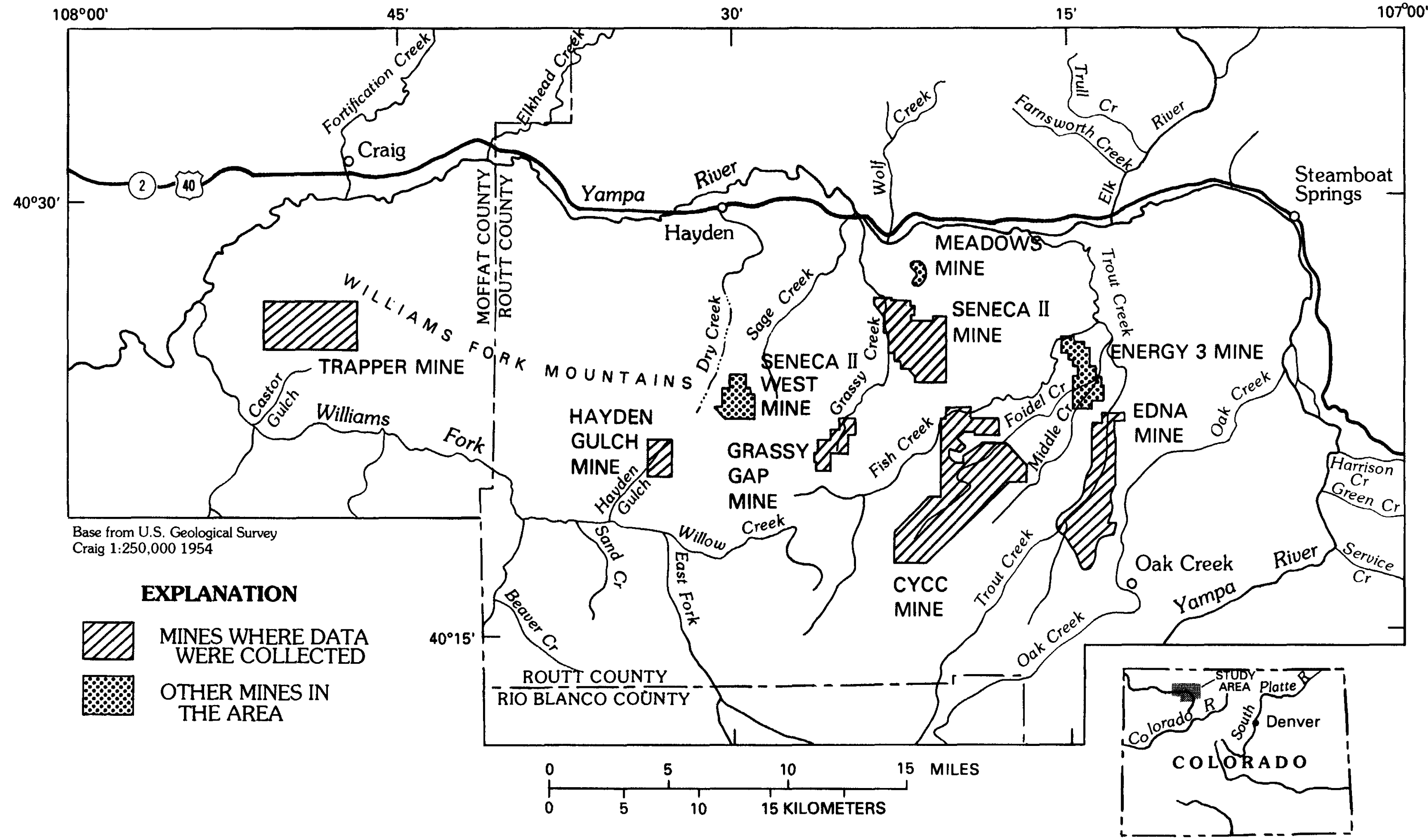

Figure 1.--Surface coal mines in northwestern Colorado.

Most of the large surface coal mines in the study area are located on geologic dip slopes, and the area-strip-mining method is used to extract the coal. Using this method, a long, rectangular pit is excavated to expose the coal seam. The crushed overburden, known as spoil, is removed using a dragline or excavation equipment and is either temporarily stockpiled to the side of the pit or is placed into an adjacent pit. After the coal is removed, the pit is shifted laterally, and the process is repeated.

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GEOMORPHIC PRINCIPLES APPLICABLE TO SURFACE-MINE RECLAMATION

Surface mining of large areas of land has resulted in disruption of many drainage basins and their associated drainage networks. These drainage basins and drainage networks evolved for millennia, and many may have approached an approximate equilibrium with the geology, climate, vegetation, and hydrology that existed prior to mining. Proper reclamation of drainage basins and drainage networks is critical to establishing a stable reclaimed landscape. Successful reclamation of a disturbed drainage basin and drainage network involves an understanding of the processes of drainage-network formation and of the interaction between the drainage network and the drainage basin.

Geomorphology of Drainage Basins

A drainage basin represents the integration of the drainage network (stream channels) and interfluvial areas that contribute runoff (divides, hillslopes, and valley floors). A drainage network is a system of stream channels that carries surface runoff from the contributing drainage area. The characteristics of a drainage network (number and length of stream channels, drainage density, drainage-network order, stream-channel dimensions, and stream-channel gradient) are controlled by the geology, geomorphology, climate, vegetation cover, surface runoff, and other physical characteristics of the drainage basin within which the drainage network has formed.

The drainage basin and drainage network are affected by, and have an effect on, drainage-basin hydrology. Carlston (1963) reported that drainage density (sum of channel-segment lengths divided by drainage-basin area), streamflow, and ground water are interrelated and reported that drainage density adjusts to facilitate the most efficient removal of flood runoff from the drainage basin. Conversely, Black (1972) reported that streamflow is a function of drainage-basin characteristics, rainfall, and soil conditions.

The morphology of a drainage basin and the processes active in it may be considered an open system. The drainage basin and drainage network constantly are responding to changes in forces affecting the system; for example, tectonism, climate, vegetation, and land use. Adjustments in a drainage network tend to fluctuate about an equilibrium condition; therefore, a drainage network occasionally may be out of equilibrium and stream channels may be unstable. Schumm and Hadley (1957) proposed the concept of erosional epicycles in drainage basins. When a stability threshold in a drainage basin is exceeded, a period of stream-channel instability (degradation or aggradation) follows until a new equilibrium condition is approached. Schumm and Hadley's study indicated that drainage-basin stability is not absolute and that unstable geomorphic conditions may exist in the drainage basin prior to degradation or aggradation of stream channels.

The drainage basin has been referred to as the basic hydrologic or geomorphic unit by Chorley and others (1984), and this concept can be applied to reclamation of surface-mined areas. Quantitative drainage-basin analysis provides a method of relating drainage-basin morphology to drainage-basin processes, thereby enabling a greater understanding of the response of a drainage basin to changes in controlling factors, such as those caused by surface mining and reclamation. Reclamation planners need to be aware of conditions that decrease drainage-basin and drainage-network stability. Once identified, some of the conditions that decrease stability can be avoided or minimized in reclamation planning.

Effects of Surface Mining

Surface mining and reclamation activities can alter a number of interrelated variables that affect the erosional stability of the land surface. Surface mining of a large area can alter entire drainage networks, and the subsequent reclamation activities can produce substantially altered geology, geomorphology, pedology, vegetation, and hydrology. Landforms are modified by erosion, a process common to all land surfaces. Over time, many landforms may become relatively stable or approach an approximate equilibrium with the controlling geologic, climatic, vegetation, and hydrologic conditions of the area. Although the geomorphology of unmined hillslopes and valley floors reflects the geologic, climatologic, vegetation, and hydrologic history of the area, the geomorphology of reclaimed surface-mined hillslopes and valley floors mostly is an artifact of spoil-material handling.

Surface mining and reclamation of large areas of land have caused changes in some of the variables that control erosion rates. Therefore, the equilibrium geomorphic conditions for reclaimed surface-mined lands may be substantially different than the equilibrium geomorphic conditions that may have existed before mining. Lithologic and structural controls on the drainage network can be irreversibly changed or obliterated when resistant lithologic units are crushed during mining. In addition, alteration of soil horizons, soil structure, and subsurface materials can affect the hydrologic properties of the unsaturated and ground-water zones and of surface runoff. Younos and Shanholtz (1980) studied soil texture and hydraulic properties of premine and reclaimed soil at a West Virginia mine and concluded that the reclaimed soils had mixed A, B, and C horizons, were compacted, and had increased bulk densities and decreased hydraulic conductivities. As a result of these changes, Younos and Shanholtz expected the reclaimed area to have less infiltration and to produce more surface runoff.

Surface mining can substantially alter vegetation type and cover. In many surface-mined areas of northwestern Colorado, mountain-shrub and aspen-forest communities that were present before mining have been converted, at least temporarily, to grass-dominated communities. Because woody plants grow more slowly and take longer to establish than herbaceous plants, grasses tend to dominate revegetated areas for a number of years.

A change in vegetation type or vegetation-cover density over a large area can have a substantial effect on snow accumulation, evapotranspiration, infiltration, and surface runoff from a drainage basin. Golding and Swanson (1986) reported that average snow-water equivalent was 20 percent greater in 20- to 30-acre clearcut areas than in the adjacent forest in an Alberta drainage basin, and Harr (1986) suggested that clearcut logging in Oregon has altered snow accumulation and melting enough to have increased peak streamflow caused by snowmelt during rainfall. Trimble and others (1987) developed a regression model relating annual streamflow and forest cover in the Southern Piedmont. They reported a 4- to 21-percent decrease in annual streamflow following land-use conversion from cropland to forest; the magnitude of streamflow change was proportional to the percentage of area converted. Trimble and others assumed the relation would apply in the opposite direction as well; increases in annual streamflow would be proportional to decreases in forest-cover area.

Alteration of geologic controls, geomorphology, pedology, and vegetation cover by surface mining can substantially affect the quantity and frequency distribution of runoff from a reclaimed drainage basin. Because the relation of the drainage network to drainage-basin characteristics is complex, reconstruction of a drainage network and stream channels to the premining conditions may not be appropriate if the geologic, geomorphic, pedologic, vegetation, and hydrologic characteristics of the reclaimed drainage basin are substantially altered.

Reclamation of Drainage Basins and Drainage Networks

Mine companies are required by law to "...restore the approximate original contour of the land..." following surface mining (Surface Mining Control and Reclamation Act of 1977, Public Law 95-87). Also, the act requires that spoil materials "...be shaped and graded in such a way as to prevent slides, erosion, and water pollution...," and that "...adequate drainage..." be provided. The act is vague concerning the quantification of approximate original contour and the definition of adequate drainage and provides no methods for the integration of the drainage network with reclaimed drainage-basin characteristics. In practice, the geomorphology of some reclaimed hillslopes and valley floors seems to have been affected by spoil-material handling and by postmining land-use considerations.

Toy and others (1987) reported that, in the long term, hillslope geomorphology (including profile, gradient, and length) is determined by hillslope processes. However, in the short term, hillslope processes are determined by hillslope geomorphology, which indicates that the geomorphology of reclaimed surface-mined areas, including hillslopes and valley floors, can have a substantial effect on erosion process and potential. Therefore, in addition to changes in geology, pedology, vegetation, and hydrology, subtle irregularities in reclaimed drainage-basin geomorphology may cause some of the recurrent rill and gully erosion observed on reclaimed surface coal mines in northwestern Colorado.

The potential for erosion of reclaimed lands can be decreased by incorporating geomorphic, hydrologic, and hydraulic principles in reclamation design. Stiller and others (1980) emphasized that the drainage basin should be the fundamental planning unit in surface-mine reclamation and recommended that a reclamation plan integrate hillslopes, stream channels, and the drainage basin so: (1) The reclaimed drainage density is at least equal to the premining drainage density; (2) reclaimed hillslope gradients are no steeper than they were before mining; and (3) stream channels have smooth, concave longitudinal profiles without irregularities. Schaefer and others (1979) summarized several studies and recommended that reclaimed land surfaces be patterned after the shapes of stable, undisturbed land surfaces; for example, concave hillslopes; concave longitudinal-stream (or valley-floor) profiles; well-defined, randomly oriented stream channels.

The recommendations by Stiller and others (1980) and Schaefer and others (1979) may provide useful criteria for surface-mine reclamation activities. However, these recommendations were based on equilibrium conditions that existed in drainage basins before surface mining. If surface mining substantially alters geology, pedology, vegetation, and hydrology, then the equilibrium drainage-basin geomorphology also may be altered. Therefore, reclaiming surface-mined land to the approximate original contours may be inappropriate, depending on the nature and extent of changes resulting from surface mining. One means of decreasing the erosion potential of reclaimed surfaced-mined lands is to identify and create equilibrium geomorphic conditions that can exist with the postmining controlling variables. Empirical studies of erosion on reclaimed surface-mined areas can provide methods for determining the appropriate geomorphology of reclaimed surface-mined drainage basins.

Drainage-network and stream-channel characteristics are components of a drainage basin that need to be incorporated in surface-mine reclamation plans. Attempts have been made to relate drainage-network characteristics directly to drainage-basin characteristics. Schumm (1956) investigated the relations among drainage area, drainage density, and stream channels. He reported that a minimum drainage area was necessary to support a unit length of channel, the constant of channel maintenance. This constant (inverse of drainage density) was determined by the erodibility of surface material and the eroding forces acting on the surface of the drainage basin. An extension of the constant of channel-maintenance concept is the zero-order drainage-basin concept. The zero-order drainage basin is the minimum drainage area from which surface runoff has sufficient force to initiate channel development. Geologic, pedologic, vegetation, and hydrologic changes resulting from surface mining and reclamation tend to decrease the size of the zero-order drainage basin (Schaefer and others, 1979).

The constant of channel maintenance, the zero-order drainage-basin size, and the drainage density are interrelated. Schaefer and others (1979) suggested that a first approximation of the postmining drainage density could be estimated from premining maps and photographs; then this drainage density could be increased somewhat for the anticipated increase in runoff caused by surface mining. However, restoring a reclaimed drainage network to a greater drainage density may produce some undesirable effects, such as increased flood peaks (Stiller and others, 1980) and steeper valley-side hillslopes (Toy and others, 1987). Therefore, Schaefer and others (1979) suggested reclaiming the drainage network to a postmining drainage density at least equal to the premining drainage density and allowing for some additional drainage-network growth as the drainage network adjusts to new equilibrium conditions in the reclaimed drainage basin. Empirical studies of reclaimed drainage basins in northwestern Colorado could facilitate identification of appropriate postmining, zero-order drainage-basin sizes, and drainage densities. Such a determination is beyond the scope of this study.

Drainage pattern, the planar configuration of main streams and tributaries in a drainage basin, is another drainage-network characteristic that needs to be determined in reclamation design. Zimpfer and others (1982) studied runoff and sediment yield from reconstructed drainage networks on a test plot using a rainfall simulator. Their objective was to determine the optimal drainage patterns for disturbed land. In the study, they reported that a reconstructed drainage network that had a dendritic pattern was most efficient at removing runoff and sediment and, therefore, was the drainage pattern associated with the most erosive conditions. To decrease erosion potential in reclaimed drainage basins, Zimpfer and others recommended reconstructing a modified drainage pattern--a dendritic drainage pattern that has most of the first-order (smallest) stream channels omitted. They reported that the first-order stream channels that had been present before the drainage basin was disturbed would regenerate, but that sediment yields from these regenerated first-order stream channels would be less than sediment yields from manmade first-order stream channels.

Zimpfer and others (1982) did not discuss the effect of potential changes in surface runoff caused by alteration of geology, pedology, or vegetation on the equilibrium drainage network. However, they did report that the premining drainage pattern may be inappropriate for reclaimed drainage basins in which the drainage-basin gradient has changed substantially. In another experimental drainage-basin study, Phillips and Schumm (1987) reported that dendritic drainage patterns were replaced by parallel drainage patterns on relatively low drainage-basin gradients (2 to 3 percent). The studies by Zimpfer and others (1982) and Phillips and Schumm (1987) indicate that modifications to premining drainage patterns may be appropriate in reclaimed drainage basins, especially if the reclaimed drainage-basin gradient is steeper than about 2 to 3 percent.

Stream-channel stability is one indication of the adequacy of surface-mine reclamation. Stable stream channels transport the water and sediment supplied from upstream without being progressively aggraded or degraded. Stream-channel morphology, or hydraulic geometry, is affected by water discharge, sediment discharge, sediment characteristics, and drainage-basin characteristics. The valley floor integrates the hillslopes and the stream channel, and, in the short term, the configuration of the valley floor affects the character of the stream channel.

There is much literature about stream-channel morphology, stream-channel hydraulics, and sediment transport in stable, or regime, channels. Many of these studies can be applied to reclamation of stream channels, although a thorough discussion of the hydraulics and sediment transport of streams in reclaimed areas is beyond the scope of this study.

Schumm and others (1984) proposed the geomorphic/hydraulic-geometry procedure to simulate equilibrium stream-channel morphology. This procedure integrates drainage-basin characteristics, hydraulic geometry, water discharge, and sediment characteristics of stream channels that are in equilibrium. Jackson and Van Haveren (1984) developed a reclamation plan for a badly disturbed reach of Badger Creek in Colorado that included channel capacity, hydraulic geometry, and bed and bank stability. They predicted that the eventual stream-channel morphology would undergo some minor changes as the design channel adjusted to natural fluctuations in streamflow and sediment transport. Toy and others (1987) summarized several other procedures for designing stable stream-channel morphology.

The geomorphic characteristics of a drainage basin have a great effect on stream-channel morphology and erosional stability. Most procedures for estimating drainage-network characteristics and stream-channel morphology are based partly or entirely on valley gradient, bed-material size, runoff, or drainage area. A common assumption is that the controlling variables are fixed; however, drainage area, valley gradient, valley-floor width, and (to some degree) bed-material size can be manipulated during the reclamation process. The erosion potential of reclaimed drainage networks and stream channels might be decreased if some of these manipulatable variables were reestablished within appropriate ranges of values. Similarly, the erosion potential of hillslopes might be decreased if hillslopes were reclaimed to appropriate profiles. This report presents some empirically determined estimates for some of these manipulatable variables.

EROSIONAL STABILITY OF RECLAIMED HILLSLOPES

Hillslopes are the inclined land surfaces below drainage divides or interfluves that often grade into hollows or valley floors. Hillslopes are important geomorphic components of a drainage basin because they compose a very large part of the landscape and are source areas for surface runoff, ground-water recharge, and sediment production. The erosional stability of reclaimed hillslopes affects sediment yield and vegetation growth on the hillslopes and, to some degree, the erosional stability of reclaimed valley floors.

Definition of Problem

Rills, and occasionally gullies, develop on many reclaimed hillslopes at surface coal mines in northwestern Colorado. Water flowing through rills can erode and redistribute large quantities of topsoil and, thus, impede vegetation growth. Water flowing through gullies also can remove topsoil and impede vegetation growth, and can mobilize the underlying spoil material as well.

Hillslope processes determine the hillslope forms that evolve over long periods of time; however, in the short term, hillslope forms determine hillslope processes (Toy and others, 1987). Therefore, the hillslope form created during reclamation can have a substantial effect on erosion processes that will be active on that reclaimed hillslope. Hillslope form in reclaimed drainage basins is created by surface-mining and spoil-regrading methods and can be manipulated to some degree. The potential for long-term erosion on reclaimed hillslopes can be decreased if hillslope forms associated with high erosion rates are not created during spoil regrading.

Hillslope Form and Process

Several studies in which erosion processes and erosion rates were related to hillslope form are applicable to reclamation of hillslopes in surface-mined areas. The Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) sometimes is used to estimate soil loss from sheet and rill erosion on hillslopes. Although this equation was developed for use on croplands and is limited in its applicability (Wischmeier, 1976), the USLE incorporates several factors contributing to hillslope erosion. These factors are rainfall, soil erodibility, hillslope length, hillslope gradient, vegetation type and cover, and surface manipulation. In the context of surface-mine reclamation, many of these factors could be controlled to some degree after spoil regrading and topsoil replacement. Erodibility of replaced topsoil is determined mostly by the texture and compaction of the replaced soil material. Once replaced, the topsoil can be ripped or plowed to decrease runoff, and mulch or other protective covers can be applied to decrease soil erodibility. Vegetation type and cover are determined by seed mix, climate, agricultural practices, and natural succession. Other surface manipulation, such as construction of contour furrows, diversion ditches, or containment structures, can be used as needed. Hillslope length and hillslope gradient are two factors that initially can be engineered, but they are virtually unchangeable once established because of the substantial cost of moving large quantities of spoil material. Appropriate hillslope length and hillslope gradient are variables that need to be determined and included in the reclamation plan before spoil regrading begins.

Meyer and others (1975) investigated soil erosion on Indiana hillslopes. They identified several factors that affected the source areas of eroded sediment, including soil properties, hillslope length, hillslope gradient, and hillslope profile (shape). Soil loss per unit area generally increased as a power function of hillslope length, and the value of the exponent in the power function (range, 0.0 to 0.9; mean, about 0.4) was determined by soil-erodibility properties. The effect of hillslope gradient on soil erosion within rills was different from the effect of hillslope gradient on the inter-rill areas. Soil erosion on inter-rill areas increased only slightly as hillslope gradient increased. In contrast, soil erosion within rills increased rapidly as hillslope gradient increased.

Hillslope profile also was important in the study by Meyer and others (1975). Four general hillslope profiles were studied: (1) Straight (uniform gradient from divide to toe), (2) convex (increasing gradient), (3) concave (decreasing gradient), and (4) complex (convex upper segment and concave lower segment). Soil loss on straight hillslopes increased gradually down the hillslope. Soil loss on convex hillslopes was less near the top of the hillslope than near the top of straight hillslopes, but soil loss on the convex hillslopes increased rapidly downslope as gradient increased. Soil loss on concave hillslopes was greatest near the top of the hillslope, but decreased downslope toward the toe of the hillslope. Deposition occasionally occurred near the toe of concave hillslopes. Soil loss on complex hillslopes was greatest near the midslope inflection between the convex and concave segments, but decreased downslope and often was replaced by deposition near the toe of the hillslope.

Hadley and Toy (1977) also studied the effect of hillslope profile on erosion rates. They used a rainfall simulator on hillslopes that had complex profiles in a badlands area of western Colorado. Their findings were similar to those of Meyer and others (1975). The greatest rates of erosion were on the straight, midslope segments between the upper convex and lower concave segments; the lowest rates were on the upper convex and lower concave segments. However, depending on rainfall intensity, either erosion or deposition was observed on the lower concave segments. Sediment eroded from upper hillslope segments was deposited in the lower concave segment when the intensity of rainfall was low. With higher rainfall intensities, sediment eroded from upper hillslope segments was transported across the lower concave segment and, occasionally, erosion occurred at the toe of the hillslope. The variability of erosion rates was greatest in the lower concave segment.

Recontouring spoil material to create complex hillslope profiles that have relatively short, steep upper segments and longer, flatter lower segments could be an effective means of decreasing hillslope erosion potential. Shorter hillslopes will produce less runoff than longer hillslopes; flatter hillslopes will produce lower runoff velocities than will steeper hillslopes. The USLE (Wischmeier and Smith, 1978) and field studies (Meyer and others, 1975; Hadley and Toy, 1977) indicated that where hillslope length and hillslope gradient are both large, erosion rates will tend to be great. The long, steep, or convex hillslopes occasionally formed during surface-mine reclamation are the antithesis of a stable, self-sustaining landform.

Toy and others (1987) stated that the preferred reclaimed hillslope has a concave or complex profile, a low hillslope gradient, and a short hillslope length. Low hillslope gradients are preferred in reclamation plans because a decrease in hillslope gradient more than compensates for an increase in hillslope length. However, if greater postmining runoff is anticipated, an increase in reclaimed drainage density may result. If reclaimed drainage density increases, shorter, steeper hillslopes probably will be created because hillslope length is inversely proportional to drainage density, and hillslope gradient is directly proportional to drainage density (Horton, 1945; Stiller and others, 1980).

Reclaimed Hillslopes in Northwestern Colorado

Erosional stability of hillslopes was studied at five surface coal mines in northwestern Colorado: Trapper, Hayden Gulch, Grassy Gap, Seneca II, and Edna (fig. 1). Data for this report were collected from 10 reclaimed hillslopes and from 4 nearby unmined hillslopes (table 1). Sites were selected for study that had morphology, aspect, and vegetation cover typical of the hillslopes elsewhere at the mines. The age of reclaimed hillslopes was at

Table 1.--*Hillslope data-collection sites*

[R, reclaimed; U, unmined; ft, feet; in., inches; %, percent; --, no age data]

Site	Site code	Land-use code	Mine and site name	Mid-slope elevation (ft)	Mean annual precipitation (in.)	Aspect (degrees)	Total hill-slope length (ft)	Hillslope gradients[a] G_{25} (%)	G_{50} (%)	G_{75} (%)	G_{max} (%)	Age (years)
1	TRDP-A	R	Trapper Mine, D-Pit, transect A	6,895	22	298	991	17	14	29	32	6
2	TRDP-B	R	Trapper Mine, D-pit, transect B	6,855	22	345	1,495	16	14	31	31	6
3	HGPO-A	R	Hayden Gulch Mine, transect A	7,540	20	224	767	16	18	28	31	4
4	GGP2-A	R	Grassy Gap Mine, Pit 2, transect A	7,770	21	304	883	14	12	10	18	7[b]
5	GGP5-A	R	Grassy Gap Mine, Pit 5, transect A	7,484	21	318	248	41	43	48	48	4
6	GGP5-C	R	Grassy Gap Mine, Pit 5, transect C	7,486	21	323	221	42	45	45	56	4
7	GGP5-E	R	Grassy Gap Mine, Pit 5, transect E	7,485	21	322	197	42	47	49	53	4
8	EDCR-A	R	Edna Mine, Center Ridge, transect A	7,630	20	287	876	6	28	30	31	6
9	EDCR-B	R	Edna Mine, Center Ridge, transect B	7,500	20	296	810	19	26	23	32	6
10	EDCR-C	R	Edna Mine, Center Ridge, transect C	7,600	20	288	939	13	27	27	30	6
11	TRWP-A	U	Trapper Mine, West Pyeatt Gulch, transect A	6,695	22	284	750	20	11	8	21	--
12	HGRA-U	U	Hayden Gulch Mine, Reference Area, transect U	7,740	20	285	850	14	17	9	18	--
13	S2LG-U	U	Seneca II Mine, Little Grassy Creek, transect U	7,010	20	26	516	22	22	33	41	--
14	S2BZ-V	U	Seneca II Mine, Buffer Zone, transect V	6,765	19	83	487	39	48	40	56	--

[a] G_{25}, G_{50}, and G_{75} represent: 25, 50, and 75 percent of the total hillslope length from the divide. G_{max} represents the hillslope gradient of the steepest hillslope segment.

[b] Age of lower hillslope segment was 8 years.

least 4 years. An ideal reclaimed hillslope study site was: (1) An older hillslope (several years since reclamation) that had been reclaimed to a final geomorphic condition; and (2) a hillslope on which vegetation, soil structure, and erosion features were allowed to evolve without subsequent rehabilitation activities, such as rill plowing, reseeding, or gully backfilling, and without temporary protection measures, such as contour furrows or diversion ditches. Subsequent rehabilitation activities or temporary protection measures would affect hillslope hydrology and the sequential development of erosion features. Without subsequent rehabilitation activities or protection measures, erosion features would evolve naturally, permitting some observations about long-term hillslope stability. Most of the reclaimed hillslopes in the study area have undergone some subsequent rehabilitation activities or protection measures. However, study sites were selected that had been minimally affected by these activities.

Midslope elevations of the reclaimed hillslopes ranged from 6,855 to 7,770 ft (table 1). Aspect of most of the reclaimed hillslopes generally was west-northwest to northwest (287-345°). At reclaimed sites, total hillslope lengths ranged from 197 to 1,495 ft, hillslope gradients at midslope (G_{50}) ranged from 12 to 47 percent, and the reclaimed hillslope ages ranged from 4 to 8 years.

Unmined hillslopes were included in the study as control sites and were selected based on their similarity to reclaimed hillslopes. The unmined hillslopes had similar elevation, hillslope length, and hillslope gradient. Two of the unmined hillslopes had aspects similar to the reclaimed hillslopes. Unmined and reclaimed hillslopes differed in two characteristics that affect the potential for rill erosion--vegetation-community stage and topsoil development. Most unmined hillslopes were predominantly grass-covered, but all had some woody shrubs, such as big sagebrush (*Artemisia tridentata*), serviceberry (*Amelanchier alnifloia*), chokecherry (*Prunus virginiana*), Gambel's oak (*Quercus gambelli*), and snowberry (*Symphoricarpos oreophilus*). These vegetation communities probably were at an advanced stage of ecological succession, having deep, well-developed roots. The reclaimed hillslopes were covered with shallow-rooted grass and were at an immature stage of succession. Topsoil profile and structure on unmined hillslopes also indicated a greater maturity than topsoil on reclaimed hillslopes.

Methods of Hillslope-Data Collection

A transect was surveyed down each hillslope from the drainage-basin divide to the hillslope toe. The cumulative hillslope length, incremental hillslope gradients, and hillslope profile (fig. 2A) were determined from this survey. A rectangular area of the hillslope that centered on the hillslope transect was delineated for additional measurements. The widths of the hillslope study areas were approximately 20 to 30 percent of the hillslope lengths.

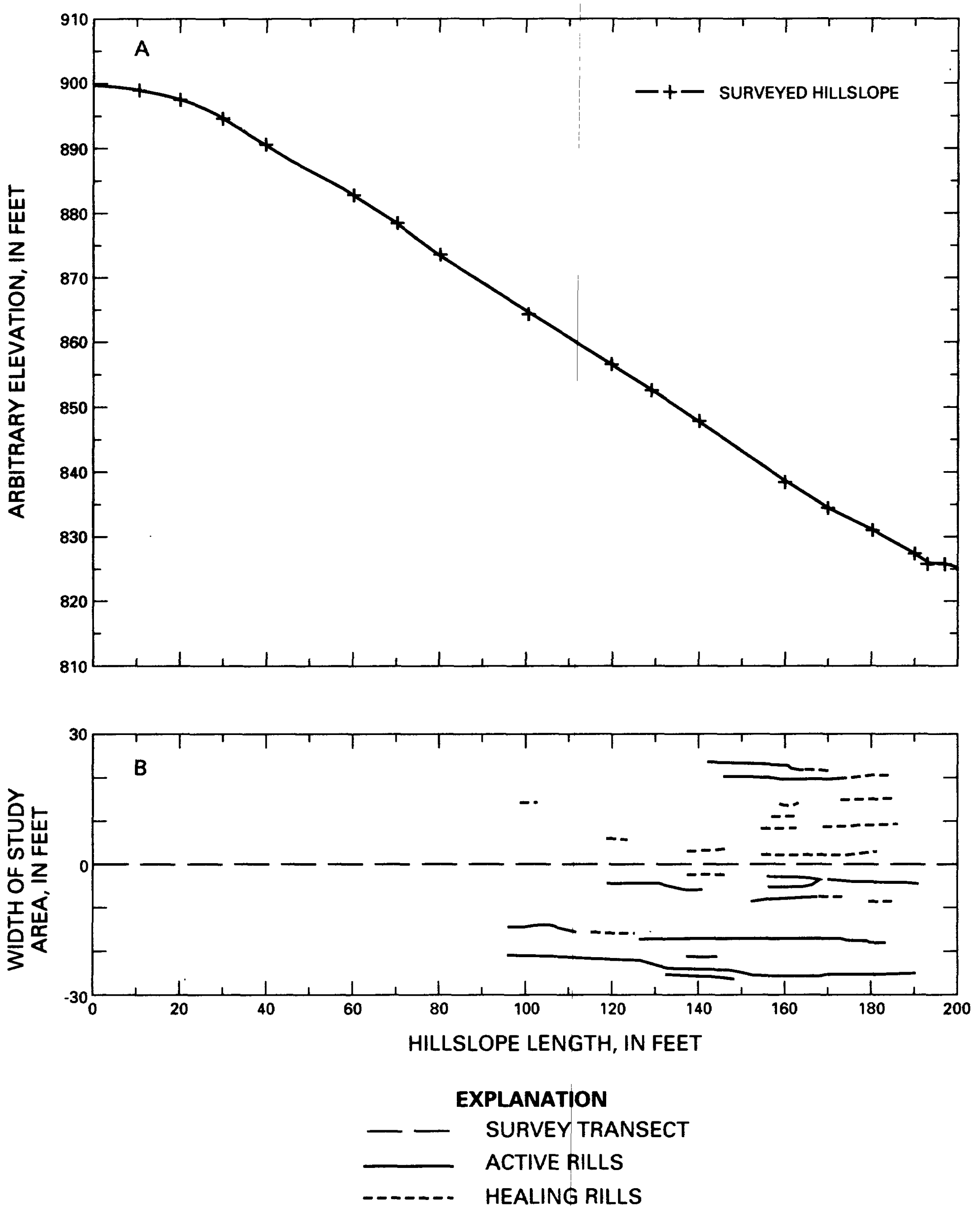

Figure 2.--*A*, Hillslope profile, and *B*, Locations of rill erosion from a reclaimed area, site GGP5-E.

Rills and gullies in the hillslope study area were mapped, and their lengths were recorded (fig. 2*B*). Two types of rills were observed--healing and active. Healing rills formerly were the source of eroded topsoil; however, at the time of the study, healing rills were inactive sediment sources, and they were being abstracted into the land surface. Healing rills had subtle smoothed features, often were discontinuous after several feet, and usually had some vegetation growing in the rill. Active rills were the source of eroded topsoil when surface runoff was generated. Active rills had pronounced angular features, often exposed coarse gravel in the soil, and usually had no vegetation growing in the rill.

Rill frequency and rill density were determined from rills mapped in the hillslope study area. Rill frequency was defined as the number of rills per unit width (100 ft) of the hillslope study area. Rills were counted that intersected lines perpendicular to the transect (across the hillslope) at 20- to 50-ft intervals along the transect. A frequency was computed at each perpendicular for healing rills, active rills, and total rills.

Rill density was defined as the sum of the lengths of all rills per unit area of the hillslope. The hillslope study area was divided into subareas that were 20 to 50 ft long (down the hillslope) and 60 to 200 ft wide (across the hillslope). Subarea length and width were approximately proportional to the total hillslope length. A rill density (sum of rill lengths, in feet per 100 ft^2 of hillslope area) was computed for each hillslope subarea for healing rills, active rills, and total rills. Rill frequencies and rill densities from reclaimed hillslopes are listed in table 5 in the "Supplemental Data" section at the back of this report.

Vegetation cover (percentage of live vegetation and litter) was determined at several locations along the hillslope transect using a 10-point vegetation counting frame. Individual plant species were not identified, but a distinction was made between grass species and woody-stemmed species.

Infiltration measurements were made at several locations along the hillslope transect to determine relative topsoil-infiltration rates. A double-capped infiltrometer was used to determine the topsoil-infiltration rates because it was portable and used relatively little water. The double-capped infiltrometer measured the steady-state infiltration rate of a ponded source of water after the topsoil had become saturated and, therefore, did not measure infiltration rates that would be typical of most rainfall. However, these infiltration measurements were appropriate in that they enabled site-to-site comparisons of infiltration characteristics that affect the rate of surface-water runoff and of erosion potential (J.E. Constantz, U.S. Geological Survey, oral commun., 1986).

Topsoil cores were collected at each infiltration-measurement site to compare infiltration and soil characteristics. Core samples were oven-dried, weighed, saturated, and reweighed to determine bulk density and porosity. The samples then were wet-sieved to determine particle-size distributions. Infiltration and soil-characteristics data are summarized in table 6 in the "Supplemental Data" section at the back of this report.

Analysis and Interpretation of Hillslope Data

There were two objectives of the investigation of hillslope erosion: (1) Determine if there were differences in the type and severity of erosion between reclaimed hillslopes and unmined hillslopes that had similar geographic characteristics, and (2) identify variables associated with high rates of erosion on reclaimed hillslopes. The purpose of the analysis was to determine the predominant factors that contribute to accelerated erosion on many reclaimed hillslopes rather than to determine the distribution function of erosion features on all hillslopes in the study area.

Measurements made on reclaimed hillslopes were compared to measurements made on unmined hillslopes (control group). Reclaimed hillslopes were included that were typical of most reclaimed hillslopes at coal mines in the study area. The unmined hillslopes were specifically selected based on their similarity to the reclaimed hillslopes in characteristics such as elevation, aspect, and general morphology. Onsite observations, graphical comparisons of variable distributions (box plots) and hillslope profiles, and t-tests were used to identify differences between the characteristics of reclaimed and unmined hillslopes. Based on t-tests, there were no statistically significant (95-percent level) differences between the reclaimed and unmined sites in midslope elevation, total hillslope length, or midslope gradient. These t-tests indicated that the reclaimed hillslopes were geographically similar to the unmined hillslopes in the study area.

The most notable difference between reclaimed and unmined hillslopes was in the type of erosion features. The predominant type of erosion on the reclaimed hillslopes in the study area was rilling. All of the reclaimed hillslopes had some rill erosion, both healing and active. Sheet erosion also was observed on a limited scale, usually at the head of active rills. Gully erosion occasionally was observed associated with specific conditions; for example, on the lower segments of long, convex hillslopes and below moisture-collecting depressions. The predominant types of erosion on the unmined hillslopes in the study area were sheet and rainsplash erosion, usually observed where grass cover or litter was absent. No rills or gullies were observed on any of the four unmined hillslopes in the study area.

The absence of rills on the unmined hillslopes could be due to the relatively small number (four) of unmined hillslopes studied. However, these four unmined hillslopes were representative of other unmined hillslopes that were geographically similar to the reclaimed hillslopes in the study area. Although it could be erroneous to conclude that all unmined hillslopes in the study area have no rills, it is reasonable to conclude that unmined hillslopes in the study area had substantially fewer rills than reclaimed hillslopes at the time of the study.

Differences between reclaimed and unmined hillslopes also were noted in several other variables. These variables could be responsible for some of the differences in rill erosion on reclaimed and unmined hillslopes. Three of the four unmined hillslopes had complex profiles: a convex upper hillslope segment, a concave lower hillslope segment, and, if present, a short, straight midslope segment (fig. 3). In contrast, many reclaimed hillslopes had a long straight midslope segment with a short convex upper hillslope segment and a short concave lower hillslope segment (fig. 2). Other reclaimed hillslopes had convex profiles for almost the entire hillslope length (fig. 4).

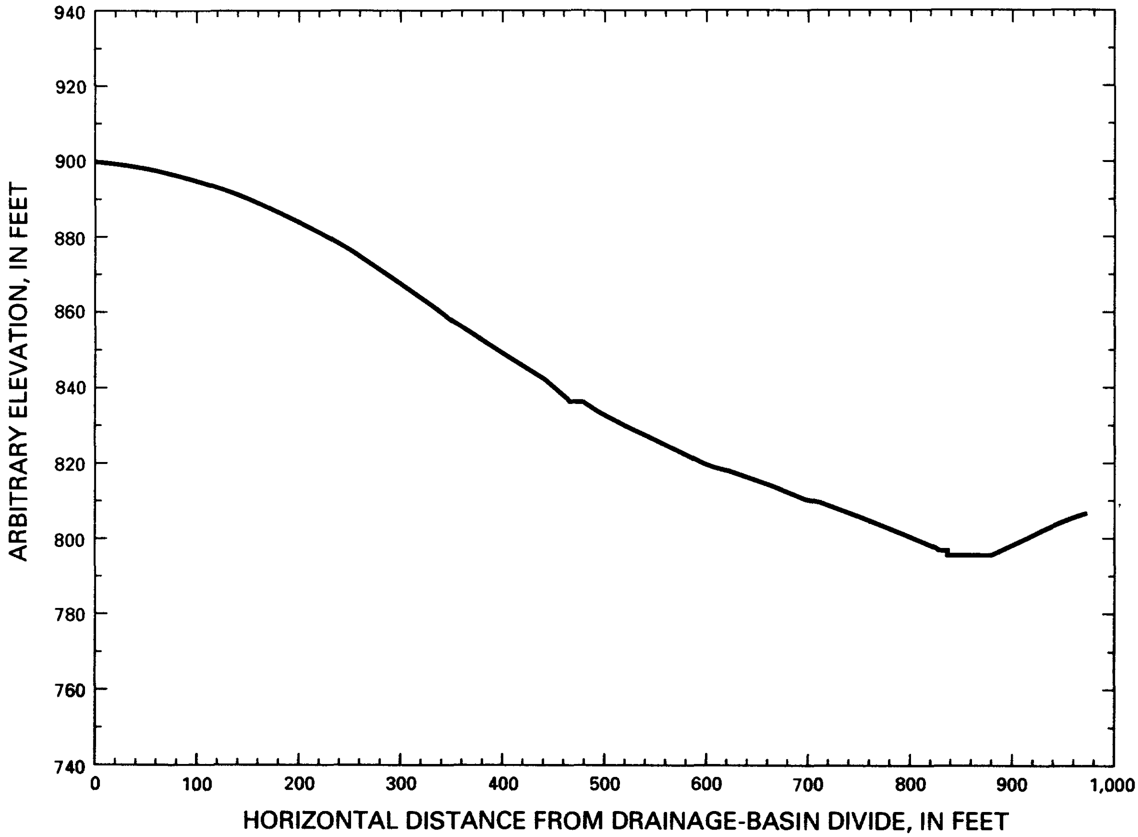

Figure 3.--Complex hillslope profile from an unmined area, site HGRA-U.

Differences in vegetation communities also were observed. The climax-vegetation (most mature) community of many unmined hillslopes in the study area was dominated by woody species. However, unmined hillslopes that had minimal forest and shrub cover were chosen as control sites because they more closely resembled the vegetation community that may develop on reclaimed hillslopes in the next decades (predominantly grass with some shrubs and few trees). All four unmined hillslopes in the study had substantial amounts of woody species in the vegetation cover. These species, including big sagebrush, serviceberry, chokecherry, Gambel's oak, and snowberry, were absent as mature plants on the reclaimed hillslopes. Reclaimed hillslopes were characterized by a herbaceous-species-dominated vegetation community (mostly grasses and forbes).

Differences in vegetation-community maturity may result in differences in the erosion potential of reclaimed and unmined hillslopes. In areas where the climax-vegetation community normally is dominated by woody species, a vegetation community dominated by herbaceous species reflects a less mature vegetation community. Because reclaimed hillslopes are dominated by herbaceous species, the reclaimed hillslopes in this study are characterized by a less mature vegetation community than the unmined hillslopes. Less mature vegetation communities may provide less protection from topsoil erosion because root systems and plant canopies are less developed than in a climax-vegetation community.

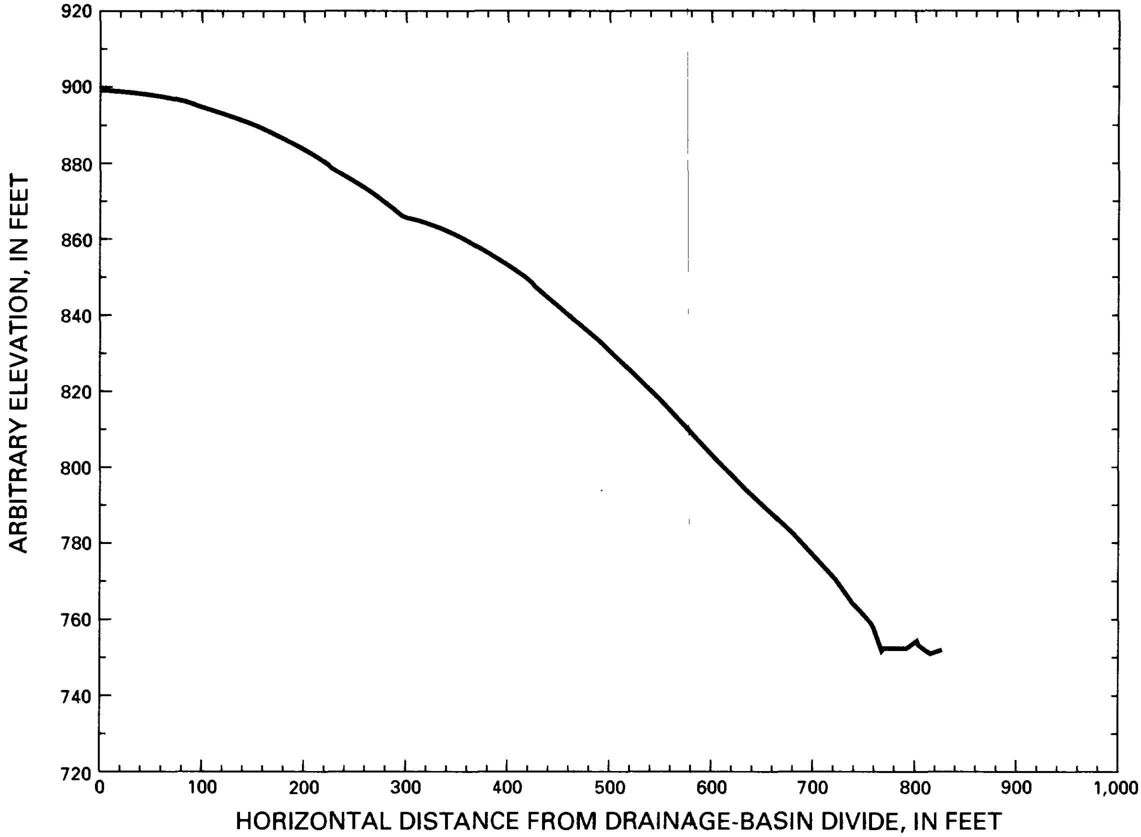

Figure 4.--Convex hillslope profile from a reclaimed area, site HGPO-A.

Topsoil-infiltration rates from the hillslope study areas varied by almost four orders of magnitude. Although the variance in the infiltration data was large, a t-test indicated that the group means from the reclaimed and unmined hillslopes were significantly different (95-percent level). Infiltration rates of reclaimed topsoils generally were an order of magnitude less than infiltration rates of unmined topsoils (fig. 5).

Topsoil bulk density and porosity have a substantial effect on infiltration rate. The t-tests indicated significant differences between the topsoils of reclaimed and unmined hillslopes in bulk density and in porosity. Differences in bulk-density and porosity data are shown by box plots in figures 6 and 7. The differences in these two physical properties between reclaimed and unmined hillslopes probably are the result of compaction that occurred when topsoils were replaced on regraded spoil hillslopes by heavy machinery. Differences in infiltration rate and bulk density for reclaimed and unmined hillslopes are shown in figure 8. Although the infiltration rate and the physical properties of topsoil varied greatly from site to site in the study area, the reclaimed hillslopes typically had lower infiltration rates and greater topsoil bulk densities.

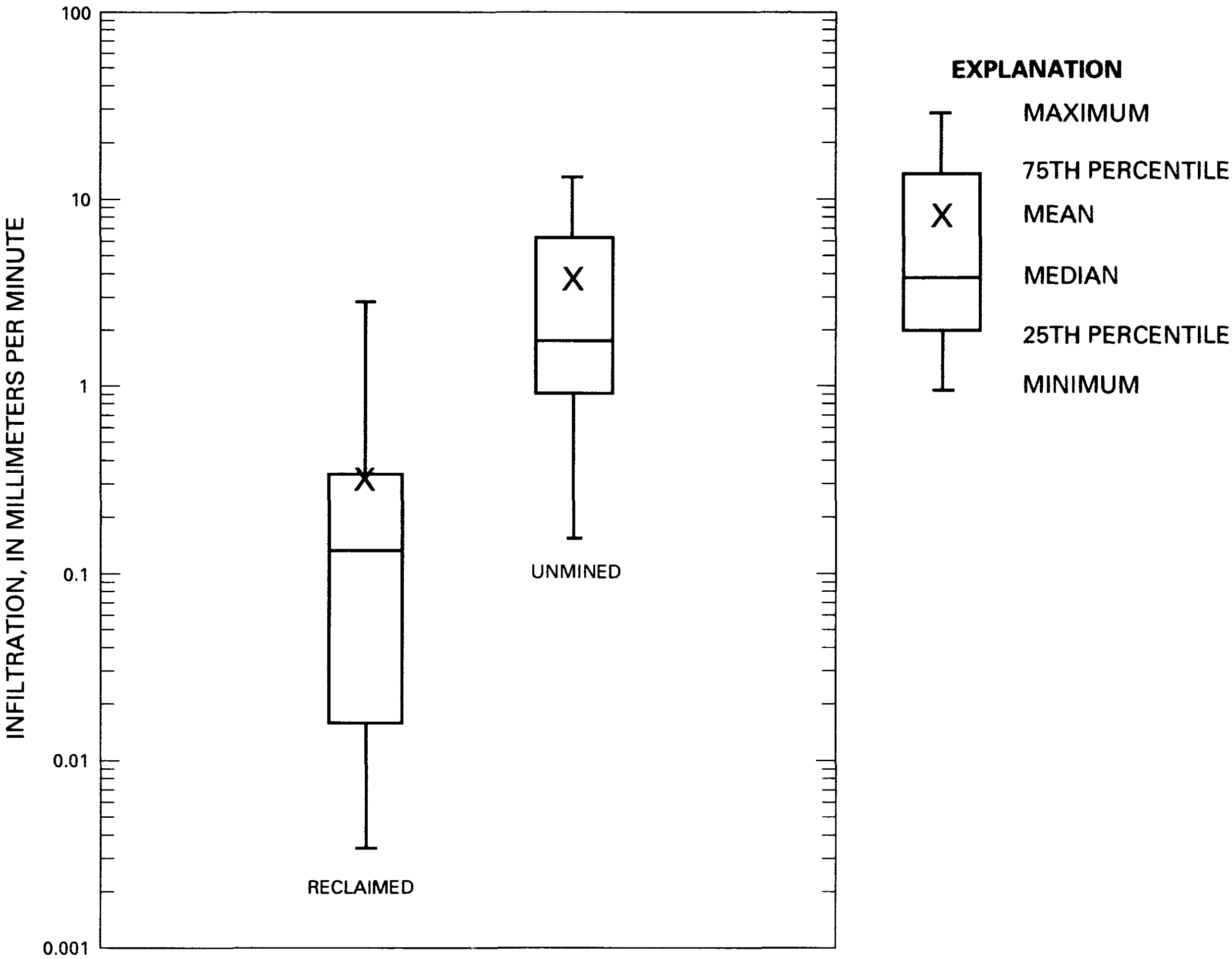

Figure 5.--Topsoil-infiltration rates from reclaimed and unmined hillslopes.

Topsoil texture (particle-size distribution) also may account for some of the variance in topsoil-infiltration rates. Topsoil particle-size distributions were determined from sieved soil samples. The percentage (by weight) of the sample finer than a specific particle size is listed for 11 particle-size categories in table 6. The t-tests indicated that there were no significant differences (95-percent level) between mean values of reclaimed and unmined hillslopes for all particle-size categories, except for medium sand (percent finer than 0.297 mm). Although there were no significant differences in the mean silt and clay content (percent finer than 0.074 mm) of the soils, box plots show that the silt and clay content of the middle 50 percent of the soil samples from reclaimed hillslopes was between about 75 and 85 percent, whereas the silt and clay content of the middle 50 percent of the soil samples from unmined hillslopes was between about 59 and 89 percent (fig. 9). The generally larger silt and clay content of soils from reclaimed hillslopes might affect the hydraulic conductivity of these soils.

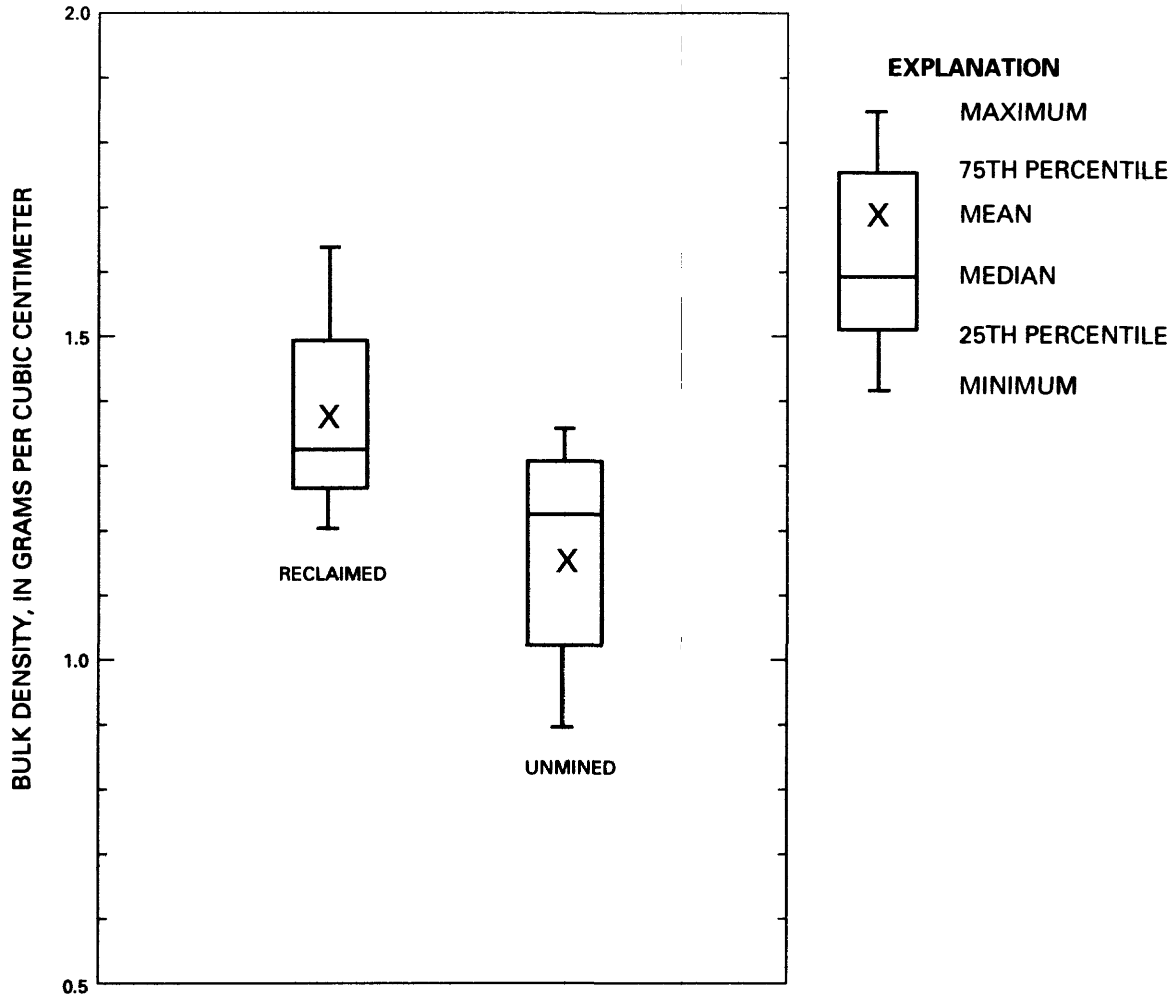

Figure 6.--Topsoil bulk density from reclaimed and unmined hillslopes.

Multiple-regression analysis was used to investigate the source of variance in the infiltration data. Soil-texture variables, bulk density, porosity, and age were included as independent variables in a stepwise-multiple-regression model. The best multiple-regression model could account for only 35 percent of variance in infiltration ($R_a^2 = 0.35$) and included two independent variables--bulk density and the silt and clay content (percent finer than 0.074 mm). The small R_a^2 may have occurred because of the large variance in infiltration rate (fig. 8) or because other variables that affect infiltration rate, such as soil chemistry or soil stratification, were not included in the analysis.

The second objective of the investigation of hillslope erosion was to identify variables associated with high erosion rates. Hillslope profiles of many reclaimed hillslopes were different from those of unmined hillslopes (figs. 3 and 4). To make a quantitative comparison of profiles from

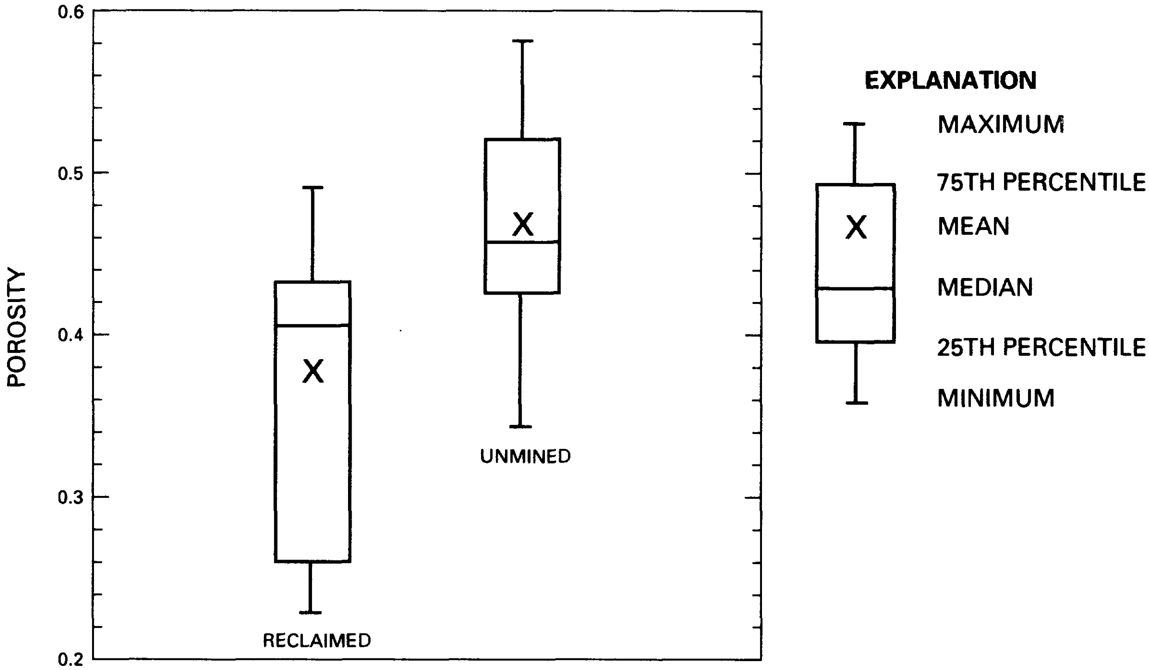

Figure 7.--Topsoil porosity from reclaimed and unmined hillslopes.

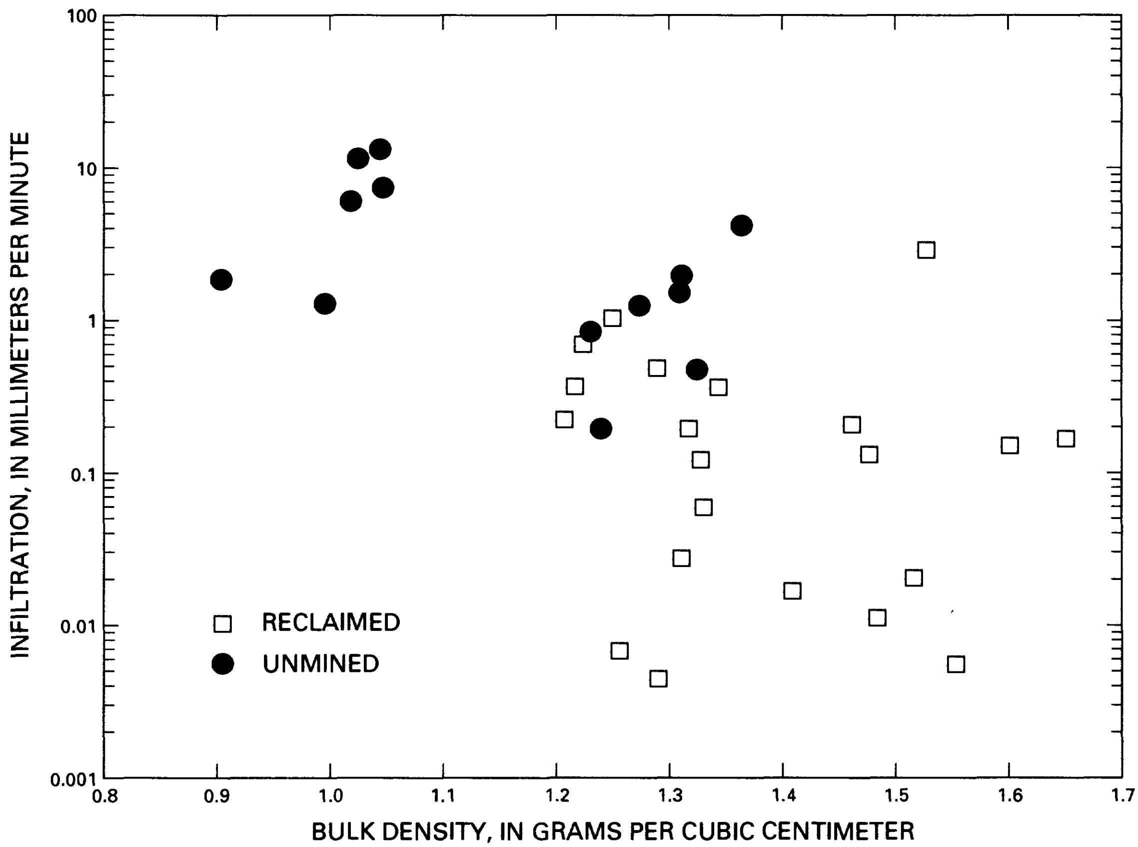

Figure 8.--Relation of topsoil-infiltration rate to topsoil bulk density.

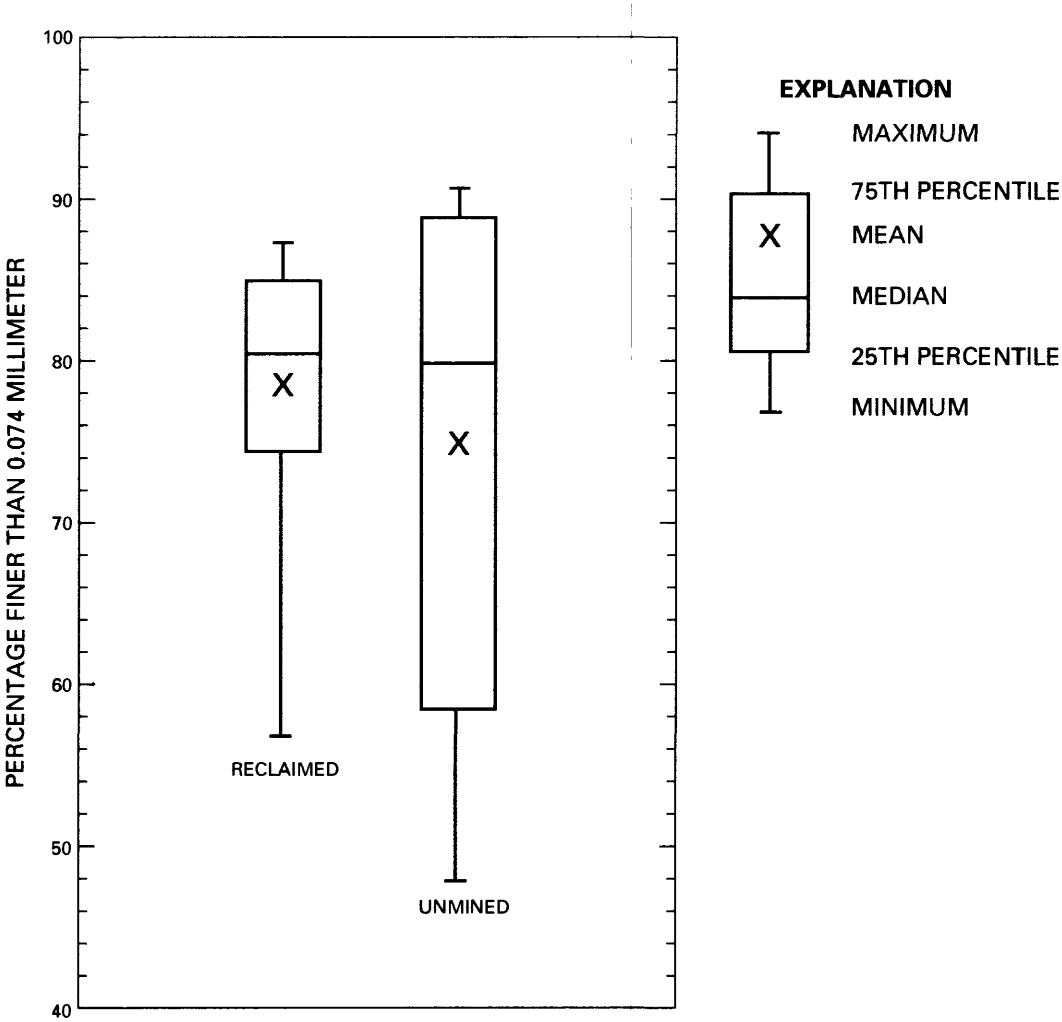

Figure 9.--Topsoil silt and clay content from reclaimed and unmined hillslopes.

hillslopes of varying length, hillslope gradient (G_s) was determined at the steepest segment and at three regularly spaced segments along the profile. The three hillslope segments were centered at points that were 25, 50, and 75 percent of the total-hillslope length from the divide. At each of these hillslope locations, a hillslope gradient was computed for a distance equal to 10 percent of the total-hillslope length (L_s). The G_s's at each hillslope location (G_{25}, G_{50}, and G_{75}) are listed in table 1. The maximum hillslope gradient (G_{max}) was determined from the steepest hillslope segment. G_s's were normalized by dividing G_{25}, G_{50}, and G_{75} by G_{max}. These normalized G_s's (for example, G_{25}/G_{max}) are plotted against normalized L_s in figure 10. Although the normalized G_s's vary considerably, the trends of the mean values indicate that the unmined hillslopes generally are steeper in the upper to midslope segments (complex hillslope profile), whereas reclaimed hillslopes are increasingly steep from top to bottom (convex hillslope profile).

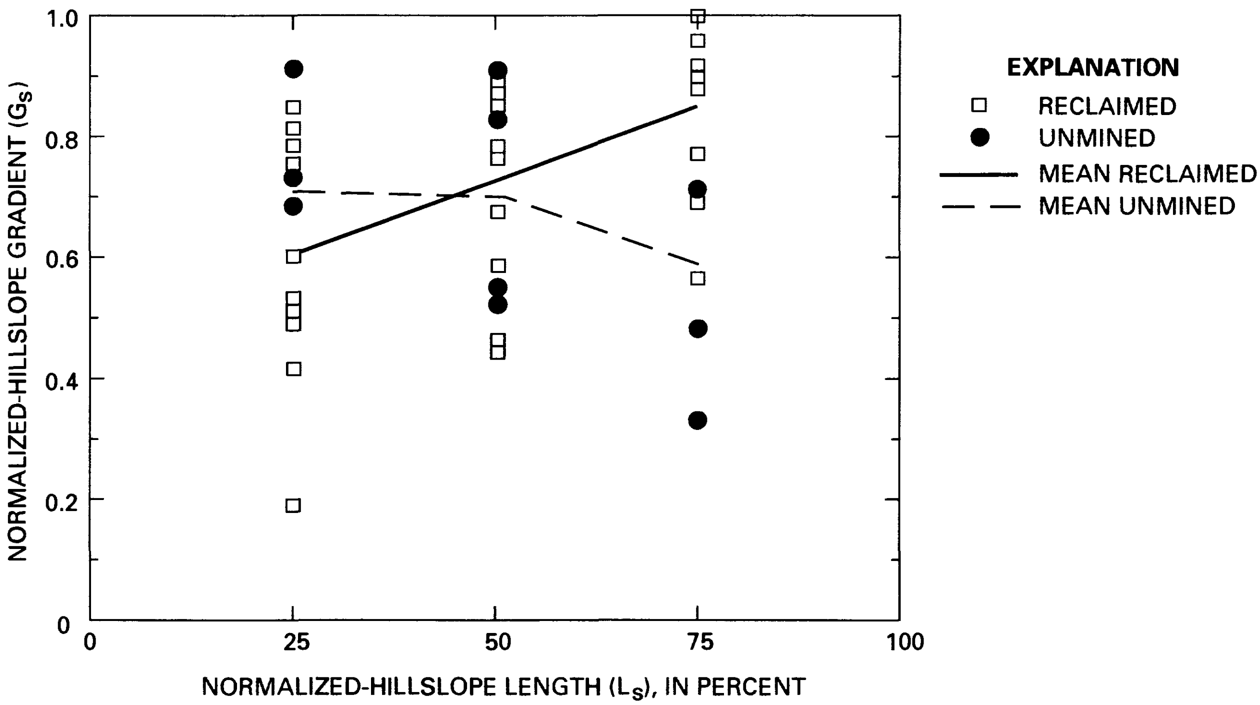

Figure 10.--Relation of normalized-hillslope gradient to normalized-hillslope length.

G_s affects runoff velocity and, therefore, the erosion potential on reclaimed hillslopes. Total-rill density (TD_r) (total-rill length per 100 ft of hillslope width) generally increased with G_s on the nine reclaimed hillslopes in the study area (fig. 11) where rills were measured (table 5). Although the greatest TD_r's occurred on the steepest hillslope segments, some steep hillslope segments had relatively few or no rills. (Note, hillslope segments that had zero TD_r are not shown on a logarithmic-scale graph). TD_r variability approaches two orders of magnitude on some steep hillslope gradients. Some of this variability may be accounted for by the effects of other variables.

Cumulative L_s is a surrogate for runoff-generating area. Longer hill slopes could be associated with greater runoff volume and, therefore, with greater erosion potential than shorter hillslopes. Rill erosion on many reclaimed hillslopes increased with increasing L_s, as other studies of hillslope processes have indicated (Meyer and others, 1975; Wischmeier, 1976; Hadley and Toy, 1977). Data from a reclaimed hillslope at the Grassy Gap Mine, site GGP5-E, indicate the effect of cumulative L_s on rill erosion (fig. 12). G_s increased rapidly from the divide and then remained relatively constant for most of the hillslope length. Gradients on the steep part of the

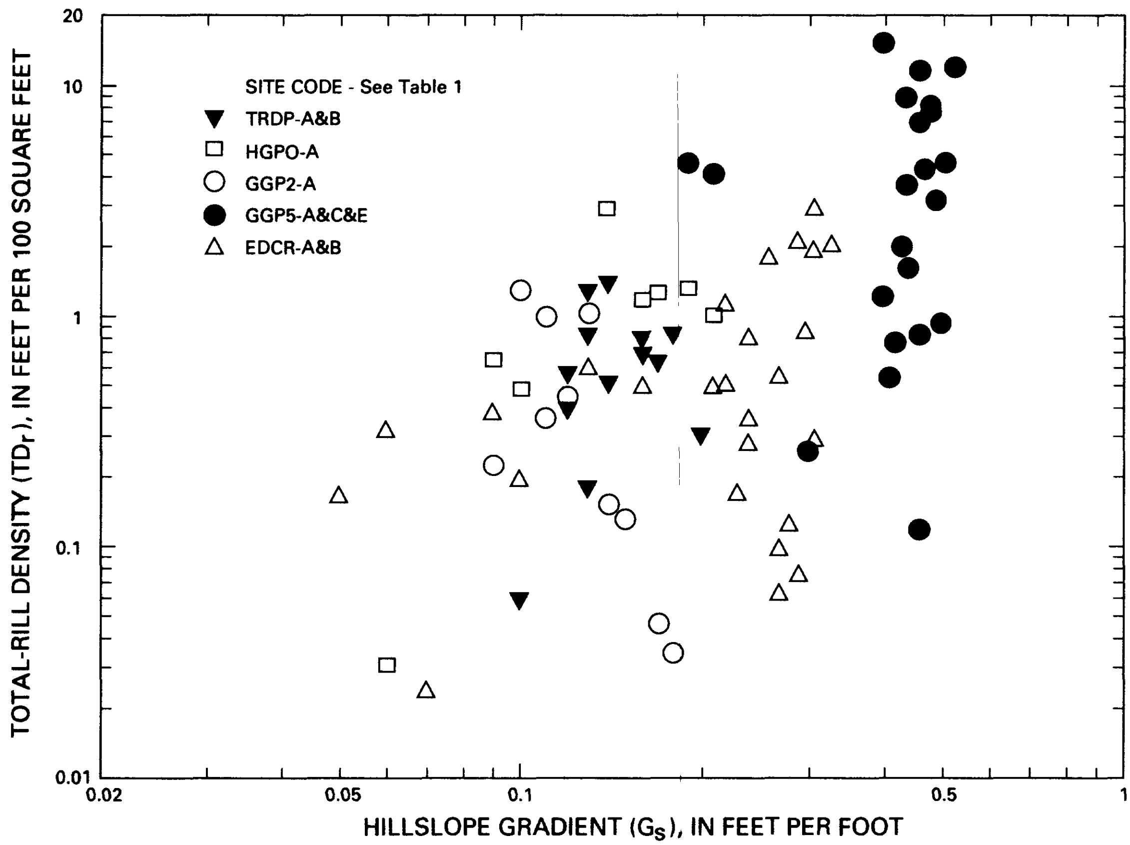

Figure 11.--Relation of total-rill density to hillslope gradient from reclaimed hillslopes.

upper hillslope segment ranged from 38 to 52 percent, but this segment was devoid of rills (fig. 2). Healing and active rills first occurred in the midslope segment. TD_r, the sum of healing-rill density (HD_r) and active-rill density (AD_r), increased steadily through the midslope segment, although the G_s remained relatively constant (range 44-53 percent). Rill densities reached a maximum on the lower hillslope segment before gradient decreased near the toe of the hillslope.

A general, downslope trend of increasing rill density was typical of most of the reclaimed hillslopes in the study area. This trend probably is due to two factors: increasing L_s (increasing runoff volume) and a constant or increasing G_s (constant or increasing runoff velocities).

Rill density and geomorphic data from subdivided areas on each hillslope (table 5) were used to examine the relation of rill erosion to hillslope morphology in greater detail. Rill densities in each subarea were compared with several separate variables. Rill densities were weakly correlated with L_s, hillslope gradient G_s, the product of hillslope length and hillslope

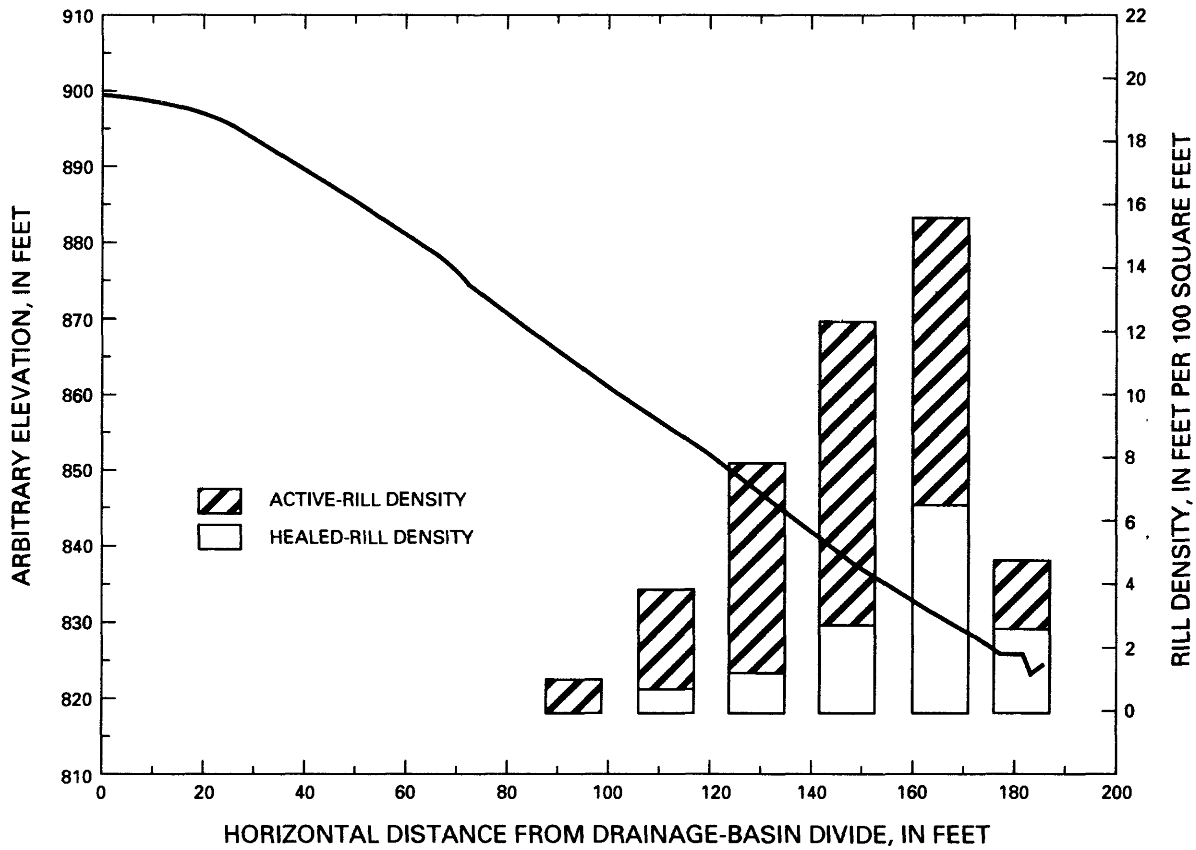

Figure 12.--Hillslope profile and rill densities from a reclaimed hillslope, site GGP5-E.

gradient (LG), and the age of the hillslope since reclamation (Y) (table 2). Logarithmic transformations (natural logarithm, base e) were made for rill densities and the geomorphic variables. Although some data were lost when variables that had zero values could not be logarithmically transformed, slightly better correlations (larger r) were observed between transformed rill densities and transformed geomorphic variables than between untransformed variables (table 2). For example, the correlation coefficient between the log of TD_r (log TD_r) and the log of LG (log LG) improved slightly (r = about 0.25, n = 81) when compared with the correlation coefficient between TD_r and LG (r = about 0.16, n = 105).

The relation of log TD_r to log LG is shown in figure 13. LG represents the combined effect of runoff volume and runoff velocity. In general, TD_r increases as LG increases; however, there is much variance in the data, and some data are clustered by mine location (GGP5 sites). The clustering of some data may be caused by differences in reclamation techniques used at different mines. For example, different topsoil reapplication and seedbed preparation techniques could affect compaction and infiltration and, as a result, erodibility and runoff.

Table 2.--*Correlation matrix of rill densities and geomorphic variables from selected reclaimed hillslopes*

[HD_r, healing-rill density; AD_r, active-rill density; TD_r, total-rill density; A/T, ratio of active- to total-rill densities; L_s, hillslope length; G_s, hillslope gradient; LG, hillslope-length, hillslope-gradient product; log, natural logarithm, base e; Y, age of hillslope since reclamation]

Variables	HD_r	AD_r	TD_r	A/T	L_s	G_s	LG	log HD_r	log AD_r	log TD_r	log A/T	log L_s	log G_s	log LG
AD_r	0.297													
TD_r	0.580	0.950												
A/T	-0.239	0.501	0.357											
L_s	0.159	-0.180	-0.102	-0.535										
G_s	0.148	0.530	0.500	0.277	0.014									
LG	0.290	0.076	0.159	-0.448	0.834	0.401								
log HD_r	0.805	0.340	0.561	-0.119	-0.099	0.236	0.138							
log AD_r	0.336	0.849	0.819	0.290	-0.215	0.762	0.381	0.573						
log TD_r	0.495	0.692	0.762	0.351	-0.227	0.548	0.059	0.798	0.960					
log A/T	-0.364	0.271	0.119	0.964	-0.428	0.316	-0.235	-0.381	0.291	0.009				
log L_s	0.221	-0.061	0.020	-0.597	0.907	-0.077	0.757	-0.042	-0.022	-0.117	-0.437			
log G_s	0.183	0.413	0.412	0.130	0.003	0.918	0.413	0.290	0.770	0.530	0.236	0.119		
log LG	0.272	0.186	0.248	-0.408	0.693	0.458	0.809	0.169	0.592	0.248	-0.173	0.829	0.653	
Y	-0.146	-0.396	-0.386	-0.262	0.496	-0.465	0.211	-0.396	-0.693	-0.539	-0.204	0.512	-0.369	0.183

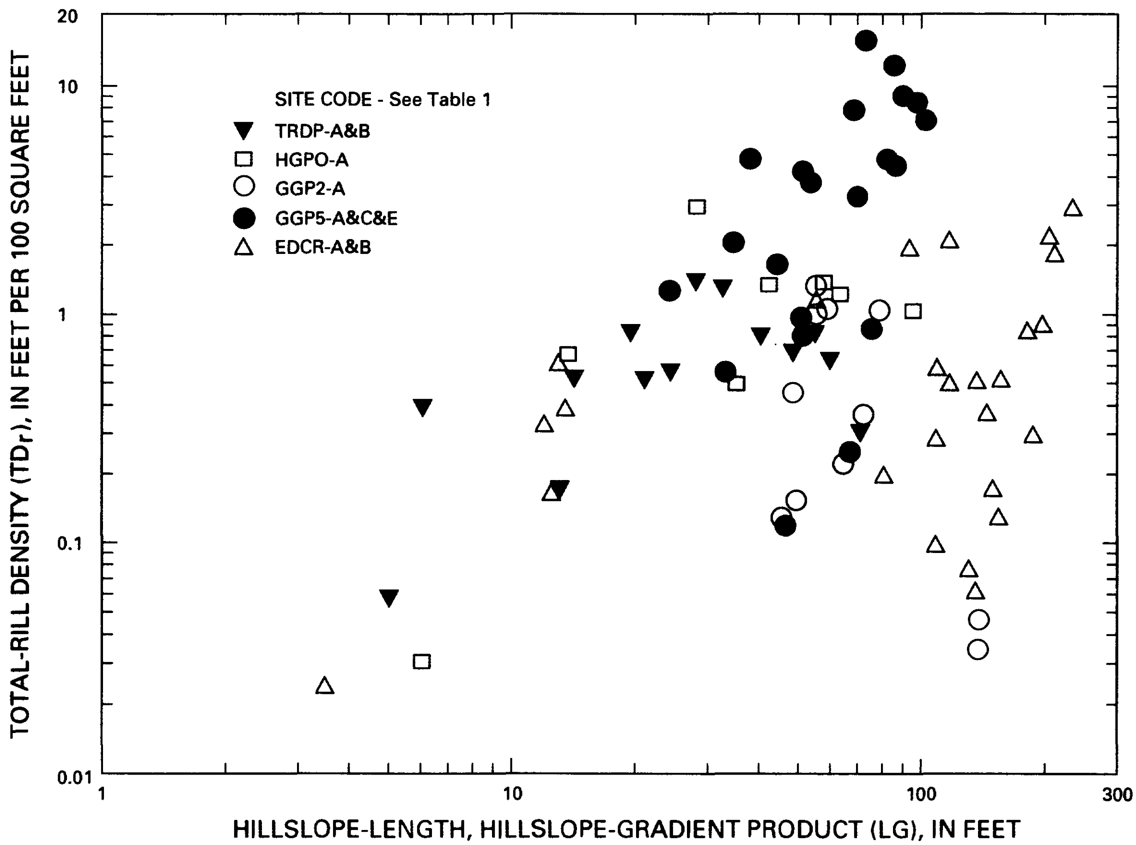

Figure 13.--Relation of total-rill density to the hillslope-length, hillslope-gradient product.

LG assumes a simple, multiplicative relation between L_s and G_s. However, different relative strengths of L_s and G_s or a nonlinear relation between L_s and G_s are other possible explanations for the data distribution shown in figure 13. The greatest TD_r's were measured at the GGP5 sites and occur for LG between about 30 and 100 ft. Reclaimed hillslopes at these sites were shorter and much steeper than reclaimed hillslopes at other sites that had LG within this range. This difference in TD_r's indicates that rill erosion on some reclaimed hillslopes may be more affected by G_s than by L_s and seems to support Toy and others' (1987) recommendation that, given a choice of reclamation options, lower G_s's are preferable to shorter L_s's because a decrease in G_s more than compensates for an increase in L_s.

Some of the clustering of rill-density data in figure 13 may be related to the age of the reclaimed hillslopes. Older hillslopes may have greater vegetation cover or root density than younger hillslopes; therefore, older hillslopes may be more resistant to rainsplash and rill erosion. Although the

EDCR and GGP2 sites have greater LG than do some of the GGP5 sites, the GGP5 sites have greater TD_r's (fig. 13). The greater TD_r's on the GGP5 sites may be due to a relatively younger age (table 1).

Stepwise-multiple-regression analyses were done to identify groups of independent variables that could account for a significant amount of variance in rill-density variables. Stepwise-multiple-regression analysis is an iterative statistical procedure that identifies individual or groups of independent variables that account for a large part of the variance in the dependent variable. Independent variables are selectively added to or deleted from the regression model until the maximum coefficient of determination, R^2, is attained. To ensure that all variables in the regression model are statistically significant, only variables for which the F statistic is significant (95-percent level) are included in the model.

The R^2 measures the proportionate decrease of total variation in the dependent variable associated with the set of independent variables in the regression model. Adding more independent variables to the model will increase R^2, but a large R^2 does not necessarily indicate that the regression model is the most appropriate model of the dependent variable. The adjusted coefficient of determination (R_a^2) accounts for the effects of the number of independent variables in the regression model and the effects of the sample size on degrees of freedom. The R_a^2 facilitates comparison of multiple-regression models developed from different numbers of independent variables and from different sample sizes.

The dependent variables in the stepwise-multiple-regression analyses were HD_r, AD_r, TD_r, and the ratio of active-rill density to total-rill density (A/T). The independent variables in the regression analyses were L_s, G_s, LG, and Y. All variables in the regression analyses, except Y, were logarithmically transformed.

Most of the multiple-regression models identified by the stepwise procedure had relatively small R_a^2 and were not considered to be good predictive models of rill density; therefore, equations of the multiple-regression models are not presented in this report. However, some conclusions concerning erosion processes on reclaimed hillslopes were made based on the independent variables included in the multiple-regression models. The best multiple-regression models for HD_r ($R_a^2 = 0.21$, n = 66); AD_r ($R_a^2 = 0.64$, n = 45); and TD_r ($R_a^2 = 0.37$, n = 81) all included the independent variables LG and Y. The sign of the exponents of LG and Y indicated that rill densities increased with LG and decreased with Y. The direct relation between rill densities and LG probably reflects the increased volume of overland flow on long hillslopes and the increased erosiveness of overland flow on steep hillslopes. The inverse relation between rill densities and Y probably reflects the decreased erodibility of hillslope materials with increased time since reclamation as the soil structure changes, vegetation cover increases, and infiltration rates increase. Similar trends in rill erosion and infiltration rates with time were observed by Collins and Dunne (1986).

The distinction between healing and active rills is noteworthy. Active rills are the source of eroded topsoil when surface runoff is generated, and they reflect the current (1986) erosional stability of a reclaimed hillslope. Healed rills formerly were the source of eroded topsoil and reflect an earlier erosional stability. It was assumed that the ratio of AD_r to TD_r on a reclaimed hillslope might decrease with time as active rills evolved into healing rills. However, no statistically significant relation between the ratio of AD_r density to TD_r and Y was identified. It also was assumed that HD_r would increase with time; however, HD_r decreased with Y (table 2). Because of rainsplash abstraction and soil creep, many once active rills could have completely healed and were undetected in the field survey.

Vegetation cover, topsoil characteristics, and infiltration rates probably have a substantial effect on hillslope runoff and rill erosion. However, inclusion of vegetation, topsoil, and infiltration data with geomorphic data did not significantly decrease the variance of rill densities. This may have been because vegetation, topsoil, and infiltration data were obtained from only a few locations on each hillslope, and the addition of these data in multiple-regression analyses decreased the overall sample size (table 5).

Two other hillslope conditions were observed that usually were associated with erosion: recent manmade disturbances, such as maintenance grading of service roads and diversion ditches, and the presence of topographic hollows or depressions where moisture collected. Periodic regrading of service roads, diversion ditches, and contour furrows often created fresh, bare soil surfaces that were prone to rill erosion. Some rills originating in these disturbed areas propagated into adjacent areas where vegetation was established.

More severe erosion was associated with inadvertently created hollows or depressions that collected moisture. These subtle geomorphic features were recognizable onsite by topography and by vegetation changes. These features were visible in longitudinal hillslope profiles (fig. 14) and in lateral hillslope transects (not shown). Gullies often originated below the outflow of these depressions when the hollows were located on the upper or midslope segments of a hillslope or when a long, steep, or convex hillslope existed below the hollow. These gullies often continued for the entire length of the hillslope.

EROSIONAL STABILITY OF RECLAIMED VALLEY FLOORS

The stability of reclaimed valley floors and stream channels may provide an indication of the overall geomorphic stability of the landforms being created by reclamation activities. Valley floors are the gently sloping surfaces in the low areas of valleys or hollows that integrate hillslopes with the drainage network. Valley floors are areas where surface runoff collects and is transported from the drainage basin, usually in stream channels, but occasionally in unchanneled flow paths. During wet conditions, water in a shallow aquifer or in the unsaturated zone also can flow to these topographically low valley-floor areas.

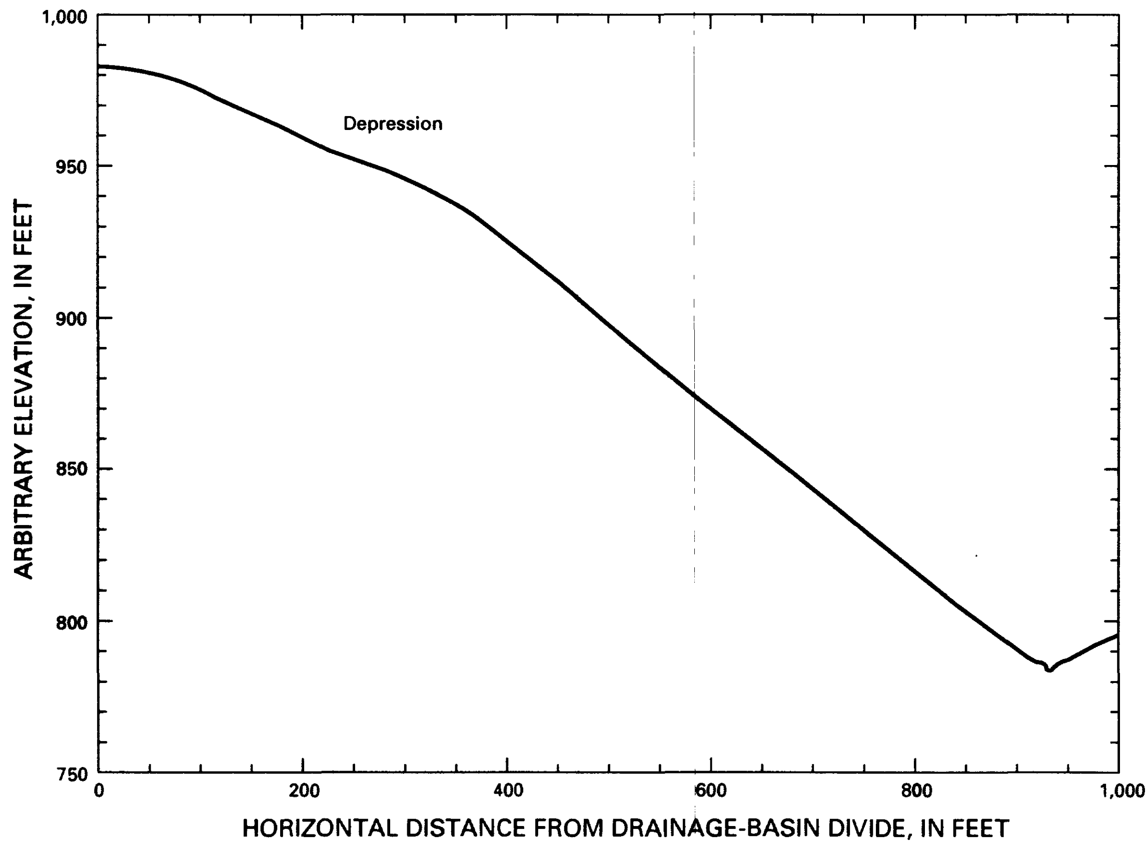

Figure 14.--Longitudinal profile of a gullied, reclaimed hillslope that has a moisture-collecting depression on the upper hillslope segment, site EDCR-C.

Stable valley-floor reaches in the study area were associated with the presence of a stable stream channel or, occasionally, with an unchanneled flow path. A stable stream channel transports the water and sediment supplied from upstream without undergoing progressive degradation, aggradation, or widespread lateral erosion. Sediment transport may involve sediment derived from upland areas, as well as sediment derived from the channel. Unstable valley-floor reaches in the study area were associated with the presence of an unstable stream channel or a gully. An unstable stream channel is in disequilibrium with the water and sediment supplied from upstream and may be actively degrading, aggrading, or laterally eroding its channel.

Definition of Problem

Gullies are a product of excessive valley-floor erosion and are created when the erosive forces (stream power) on a valley floor exceed the resistant forces (material strength, critical particle size, and sediment supply). Gullies on reclaimed valley floors are a serious problem because: (1) Large quantities of topsoil and spoil material are mobilized, (2) sedimentation rates may be increased downstream, (3) water quality may be affected downstream, and (4) local base-level lowering may propagate rill and gully erosion upstream to nearby tributaries and to nearby hillslopes.

The morphology of naturally evolved valleys is a result of hillslope and fluvial processes and can be considered to be a product of the geology, pedology, vegetation, and hydrology in the drainage basin. The configuration of the valley floor affects and is affected by the stream channel. Surface mining may alter many geologic, pedologic, vegetation, and hydrologic conditions. Also, the morphology of reclaimed valleys often is produced arbitrarily by spoil-material handling. Compaction of spoil and topsoil and replacement of woody vegetation by grasses tend to produce greater surface runoff. Replacement of bedrock controls by unconsolidated spoil material decreases the resistance of the valley floor to erosion. Subtle irregularities in surface morphology, such as steep or constricted valley reaches, increase the erosiveness of surface flow. Because changes in spoil and topsoil physical properties and in vegetation type are inevitable consequences of surface mining, the potential for valley-floor erosion might be decreased by creating a reclaimed land surface where unstable morphologies are eliminated.

Drainage-Basin Form and Process

Surface mining produces a new set of drainage-basin conditions to which the reclaimed drainage network must adjust. These new conditions will affect: (1) The size of zero-order drainage basins; (2) the number, length, and pattern of stream channels; (3) channel and valley morphology; and (4) sediment production. Several studies relating drainage-basin form to process are applicable to reclamation of surface-mined drainage basins.

Schumm and Hadley (1957) reported that many rejuvenated western stream channels were degrading in response to cyclically unstable conditions that had been created in the drainage basin. Parker (1977) modeled the evolution of a drainage network in a rejuvenated drainage basin and documented the resulting sediment yield in an experimental drainage basin. Based on these studies and additional experimental drainage-basin data, Zimpfer and others (1982) proposed a method for designing drainage networks for reclaimed surface-mined areas that would result in minimal channel (or gully) erosion. Zimpfer and others also reported that some additional adjustment in the drainage network could be expected after reclamation. This method has not been tested for a large area, and it is not clear how surface-mine-induced changes in spoil-material and topsoil properties, vegetation, and surface runoff can be incorporated in the method.

The likelihood that a stable drainage network will evolve and become self-perpetuating would be greater if a stable drainage-basin form is reconstructed in a surface-mined area. Because large reclaimed areas are not uniformly planar, the reclaimed surface morphology becomes the initial drainage-basin form and has a strong effect on the configuration and character of the drainage network. On a smaller scale, the reclaimed valley morphology affects the stability of the stream channel located on the valley floor.

Creation of an appropriate valley morphology is critical to the successful reclamation of surface-mined areas. Valleys are topographic areas where moisture and surface water is collected and where stream channels usually form. The stability of the valley floor and, hence, the stability of the stream channel, is determined partly by the contributing drainage area and by the valley morphology. Bradley (1980) studied the effect of drainage area, valley gradient, and valley-floor width on gully formation in small ephemeral drainage basins in northeastern Colorado. Bradley's study was the basis for development of the geomorphic stream-power-threshold approach for identifying the relative stability of valley floors in small drainage basins (Schumm and others, 1980). In this approach, stream power was estimated using geomorphic variables instead of hydraulic variables. The geomorphic stream-power threshold was defined as a function of the product of drainage area and the ratio of valley gradient to valley-floor width. When valley floors were too steep or too narrow for a specific drainage area, threshold conditions were exceeded, and gully erosion was likely to occur.

The geomorphic stream-power threshold may be applicable in assessing the relative stability of surface-mined valley floors. Threshold conditions on reclaimed valley floors could be exceeded by: (1) Increasing the contributing drainage area, (2) increasing valley gradient locally, or (3) decreasing valley-floor width. Because drainage area, valley gradient, and valley-floor width are all variable in the reclamation process, the geomorphic stream-power threshold also may be useful in reclamation planning of large surface-mined areas.

Reclaimed Valley Floors in Northwestern Colorado

Valley-floor stability was studied in 10 reclaimed drainage basins at 4 surface-coal mines in northwestern Colorado: the Trapper, Hayden Gulch, Seneca II, and CYCC Mines (table 3). A total of 27 valley-floor reaches in these reclaimed drainage basins were surveyed onsite (table 4). Valley-floor reaches selected for study represented a variety of geomorphic conditions observed at reclaimed surface coal mines in the study area. These reaches were minimally affected by post-reclamation activities (regrading of land surfaces and construction of diversion ditches and check dams) and, as such, exemplified land-maintenance practices that probably will exist after all mine-company maintenance ends in the near future (5 to 10 years). Reclamation of an entire surface-mined drainage basin usually occurred over a period of more than 1 year. Most of the area of a drainage basin in which study sites were located had a minimum age of 3 years.

Some geomorphic data also were collected for the premine condition of 9 of the 10 reclaimed drainage basins. These data included drainage-network order, drainage area (A_d), total stream-channel length (L_c), drainage density (D_d) (table 3), valley gradient (G_v), valley-floor profile, and hypsometric curve. At the time of this study, all premine sites had been mined and were reclaimed. Geomorphic conditions at premine sites were determined from topographic maps and aerial photographs prepared before the sites were mined. Seven valley-floor reaches in unmined drainage basins were included in the study for comparison (table 4). The unmined drainage basins had elevations, orientations, and A_d's similar to most of the reclaimed and premine drainage basins in the study area.

Table 3.--*Drainage-basin characteristics from selected premine, reclaimed, and unmined drainage basins*

[Pre, premine; Rec, reclaimed; Unm, unmined; ft, feet; ft/acre, feet per acre]

Drainage basin code	Land-use code	Mine	Drainage-basin name	Drainage-network order	Drainage-basin area, A_d (acres)	Total stream-channel length, L_c (ft)	Drainage density, D_d (ft/acre)
EBZ-P	Pre	Trapper	East Buzzard Gulch	2	361	4,826	13.4
EBZ-R	Rec	Trapper	East Buzzard Gulch	2	320	3,522	11.0
COY-P	Pre	Trapper	Coyote Gulch	1	193	2,408	12.5
COY-R	Rec	Trapper	Coyote Gulch	1	76.8	2,101	27.4
ENN-U	Unm	Trapper	East No Name Gulch	1	154	3,722	24.2
P20-P	Pre	Hayden Gulch	Basin P20	2	21.1	1,542	73.1
P20-R	Rec	Hayden Gulch	Basin P20	2	18.6	1,584	85.2
P30-R	Rec	Hayden Gulch	Basin P30	1	17.9	834.2	46.6
DGT-U	Unm	Hayden Gulch	Dowden Gulch Tributary	1	195	5,032	25.8
S60-P	Pre	Seneca II	Basin S60	2	51.2	2,239	43.7
S60-R	Rec	Seneca II	Basin S60	1	85.1	1,616	19.0
S70-P	Pre	Seneca II	Basin S70	1	56.3	2,039	36.2
S70-R	Rec	Seneca II	Basin S70	1	37.8	1,169	30.9
S20-U	Unm	Seneca II	Basin S20	1	28.8	1,072	37.2
S40-U	Unm	Seneca II	Basin S40	1	13.4	813.1	60.7
S90-U	Unm	Seneca II	Basin S90	1	23.7	961.0	40.5
311-P	Pre	CYCC	Basin 31-1	1	168	2,783	16.6
311-R	Rec	CYCC	Basin 31-1	2	123	4,198	34.1
312-P	Pre	CYCC	Basin 31-2	1	34.6	760.3	22.0
312-R	Rec	CYCC	Basin 31-2	1	71.7	2,666	37.2
071-P	Pre	CYCC	Basin 7-1	1	91.5	1,917	21.0
071-R	Rec	CYCC	Basin 7-1	2	62.1	3,295	53.1
072-P	Pre	CYCC	Basin 7-2	1	126	2,286	18.1
072-R	Rec	CYCC	Basin 7-2	2	49.3	3,268	66.3

Table 4.--*Geomorphic data from surveys of selected valley-floor reaches in reclaimed and unmined drainage basins (Modified from Elliott, 1989)*

[Rec, reclaimed; Unm, unmined; St, stable; Us, unstable; He, healing; ft/ft, feet per foot; ft, feet; acres/ft, acres per foot; --, not computed; NC, no channel]

Site code	Land-use code	Stability code	Mine	Drainage-basin name	Contributing drainage area (acres)	Valley gradient, G_v (ft/ft)	Valley-floor width, W_v (ft)	Area-gradient index, AGI (acres)	Valley-erosion index, VEI (acres/ft)	Channel width, D (ft)	Channel depth, D (ft)
EBZ-1	Rec	Us	Trapper	East Buzzard Gulch	20.5	0.164	28	3.4	1.3	2.6	2.1
EBZ-3	Rec	St	Trapper	East Buzzard Gulch	12.8	0.228	40	2.9	0.86	NC	NC
EBZ-4	Rec	St	Trapper	East Buzzard Gulch	80.6	0.108	46	8.7	0.92	7.7	0.8
EBZ-5	Rec	Us	Trapper	East Buzzard Gulch	96.0	0.131	45	13	1.0	4.5	1.8
EBZ-7	Rec	St	Trapper	East Buzzard Gulch	186	0.0355	46	6.6	0.87	8.5	0.4
EBZ-9	Rec	Us	Trapper	East Buzzard Gulch	320	0.0303	40	9.7	1.1	13	2.5
COY-1	Rec	St	Trapper	Coyote Gulch	5.76	0.0819	38	0.47	0.64	NC	NC
COY-2	Rec	St	Trapper	Coyote Gulch	8.96	0.160	56	1.4	0.53	NC	NC
COY-4	Rec	Us	Trapper	Coyote Gulch	55.7	0.148	33	8.2	1.3	25	2.6
EBZ-2	Unm	St	Trapper	East Buzzard Gulch	31.4	0.179	51	5.6	--	NC	NC
ENN-1	Unm	St	Trapper	East No Name Gulch	90.2	0.125	57	11	--	6.5	1.3
P20-1	Rec	St	Hayden Gulch	Basin P20	11.5	0.0309	30	0.36	0.77	5.5	0.3
P20-2	Rec	Us	Hayden Gulch	Basin P20	13.4	0.0672	27	0.90	1.0	1.5	1.0
P20-3	Rec	Us	Hayden Gulch	Basin P20	15.4	0.0904	26	1.4	1.1	2.0	0.6
P30-1	Rec	St	Hayden Gulch	Basin P30	10.9	0.0561	32	0.61	0.80	NC	NC
P30-2	Rec	St	Hayden Gulch	Basin P30	15.4	0.0502	65	0.77	0.41	NC	NC
DGT-1	Unm	St	Hayden Gulch	Dowden Gulch Tributary	12.2	0.0868	56	1.1	--	NC	NC
DGT-2	Unm	St	Hayden Gulch	Dowden Gulch Tributary	33.9	0.161	36	5.5	--	6.0	0.8
S60-5	Rec	Us	Seneca II	Basin S60	65.9	0.180	55	12	0.81	6.7	1.8
S70-5	Rec	St	Seneca II	Basin S70	37.8	0.0172	45	0.65	0.57	7.5	0.4
S70-6	Rec	Us	Seneca II	Basin S70	38.4	0.218	35	8.4	1.2	5.8	0.9
S20-9	Unm	St	Seneca II	Basin S20	28.8	0.127	45	3.7	--	4.5	0.4
S40-8	Unm	He	Seneca II	Basin S40	12.8	0.107	22	1.4	--	4.3	1.8
S90-9	Unm	He	Seneca II	Basin S90	22.4	0.0686	18	1.5	--	5.0	1.8
311-1	Rec	St	CYCC	Basin 31-1	11.5	0.102	20	1.2	1.4	NC	NC
311-3	Rec	Us	CYCC	Basin 31-1	33.9	0.156	20	5.3	1.9	3.5	0.8
311-7	Rec	Us	CYCC	Basin 31-1	88.3	0.0988	36	8.7	1.2	7.0	0.6
311-7a	Rec	St	CYCC	Basin 31-1	88.3	0.0249	36	2.2	0.90	--	--
311-9	Rec	Us	CYCC	Basin 31-1	117	0.169	37	20	1.3	7.8	3.4
312-5	Rec	Us	CYCC	Basin 31-2	51.8	0.101	36	5.2	1.1	2.1	0.7
312-7	Rec	St	CYCC	Basin 31-2	64.6	0.0599	48	3.9	0.76	2.1	0.1
071-7	Rec	St	CYCC	Basin 7-1	45.4	0.0319	30	1.4	0.99	3.5	0.5
071-9	Rec	Us	CYCC	Basin 7-1	48.0	0.138	23	6.6	1.7	13	1.3
072-9	Rec	Us	CYCC	Basin 7-2	41.6	0.0758	34	3.2	1.0	9.9	0.8

Reclaimed drainage basins in the study area had A_d's that ranged from 17.9 to 320 acres (table 3), and all drainage basins were drained by first- or second-order drainage networks as defined by Strahler (1957, p. 914). Drainage networks were defined by the extent of identifiable, mapped stream channels on topographic maps (scale 1:4,800 or 1:6,000). Soil in the reclaimed drainage basins had been disturbed by removal from the original location, storage in stockpiles, and reapplication by heavy machinery. These activities tended to homogenize the composition and to compact the structure of the soil. The changes in topsoil physical characteristics (increased bulk density and decreased porosity) and in topsoil-infiltration characteristics (decreased infiltration rates) described in the "Analysis and Interpretation of Hillslope Data" section probably are valid for the entire drainage basin. Vegetation in reclaimed drainage basins was almost entirely perennial grasses and forbs. Attempts have been made to transplant or seed woody species, but these species were a negligible percentage of the existing vegetation cover. The valleys of reclaimed drainage basins had no bedrock control and were re-created from the regraded, crushed spoil material. The cross sections of many of these reclaimed valleys often were narrow and v-shaped, depending on the profile of the adjacent valley-side hillslopes.

Unmined drainage basins in the study area had A_d's that ranged from 13.4 to 195 acres, and all drainage basins had first-order drainage networks (table 3). Soil and vegetation in the unmined drainage basins were diverse and varied with elevation, geologic parent material, and microclimate. A description of soil and vegetation types at the Trapper Mine is included in a report by Western Ecological Services Company (1986), and much of this information was presumed applicable to other mines in the study area. Soil types at the Trapper Mine were predominantly deep, well-drained loams, or silty-clay loams, that had minor quantities of clay loam, sandy-clay loam, and gravelly loam. Rock outcrops and colluvial deposits composed about 6 percent of the unmined land at the Trapper Mine at the time of the survey. Vegetation types included mountain shrub, aspen, big sagebrush, and grassland communities. The valleys of unmined drainage basins generally were parabolic in cross section. Many valleys in unmined drainage basins were formed on geologic dip slopes where the valley gradient was approximately equal to the geologic dip. However, some valleys interesected dipping sedimentary outcrops where the valley gradient was greater than or less than the geologic dip. Outcropping sedimentary rocks had a structural control on the valley longitudinal profile and cross section.

Methods of Valley-Floor Data Collection

Geomorphic characteristics for each drainage basin and valley-floor reach were obtained from onsite surveys and topographic maps. These characteristics included: A_d, L_c, D_d, G_v, valley-floor width (W_v), and area-gradient index (AGI). Longitudinal and transverse valley-floor surveys were made to determine G_v, W_v, and channel dimensions (table 4). G_v was computed over a distance of about 200 ft on the longitudinal valley-floor survey. This distance was about the same as the horizontal distance between mapped contour lines, but the resolution and detail of topography in the surveyed valley-floor profile was far greater than that in the valley-floor profile determined from adjacent map contours.

W_v, the horizontal distance between the lateral limits of the valley floor, was estimated onsite and confirmed from a plot of the transverse valley-floor profile. The lateral limits of the valley floor were identified as the noticeable flattening of the toe of the adjacent valley-side hillslopes. Identification of valley-floor limits was somewhat subjective in several reclaimed valleys because of topographic irregularities caused by spoil-material handling.

A_d, L_c (table 3), and contributing drainage area (table 4) were determined using a digital planimeter. Most of the study reaches were located on 1:4,800- or 1:6,000-scale topographic maps, but two study reaches (DGT-1 and DGT-2) were located on a 1:24,000-scale map.

Reclaimed valley-floor reaches were classified as stable or unstable, depending on the geomorphic condition of the stream channel or gully on the valley floor. Although stability classification was somewhat subjective and was based on an observation at a point in time, the principal criterion for determining stability of a valley-floor reach was whether a channel was progressively eroding its bed or banks. Stable reclaimed valley-floor reaches had channels that were characterized by sloping, vegetated banks, large width-to-depth ratios (mean = 16.0, minimum = 7.0, maximum = 21.2), and relatively fine sediment in the channel bed and banks. Some stable reclaimed valley-floor reaches that had relatively small contributing drainage areas (less than about 15 acres) had no developed channels (sites EBZ-3, COY-1, COY-2, P30-1, P30-2, and 311-1) (table 4). Unstable reclaimed valley-floor reaches had degraded, gullied channels that were characterized by steep banks devoid of vegetation, small width-to-depth ratios (mean = 5.5, minimum = 1.2, maximum = 12.4), and coarse spoil material exposed in the channel bed and banks. Most unmined valley-floor reaches in the study area were classified as stable. Two unmined valley-floor reaches had evidence of past gullies; however, at the time of the study (1987), the channels seemed to be healing and stable.

Analysis and Interpretation of Valley-Floor Data

Mine operators have reconstructed drainage basins, valleys, and drainage networks with varying success; however, a better understanding of the factors that determine the erosional stability of reclaimed drainage basins and valleys could improve reclamation success. In most reclaimed drainage basins, stream channels were allowed to develop naturally on the recontoured surfaces, but some channels were established mechanically during reclamation. The drainage area, drainage network, drainage density, and drainage-network order of most reclaimed drainage basins have been noticeably altered from premine conditions. In addition to changes in these planar features, changes also have occurred in the distribution of land mass within individual basins.

Contiguous drainage basins 31-1 and 31-2 illustrate some of the mining-related changes in planar features (fig. 15). Before mining, the A_d was 168 acres in basin 31-1 and 34.6 acres in basin 31-2 (table 3). The D_d defined as the L_c divided by A_d, was 16.6 ft/acre in basin 31-1 and 22.0 ft/acre in basin 31-2. The combined A_d of both basins was about

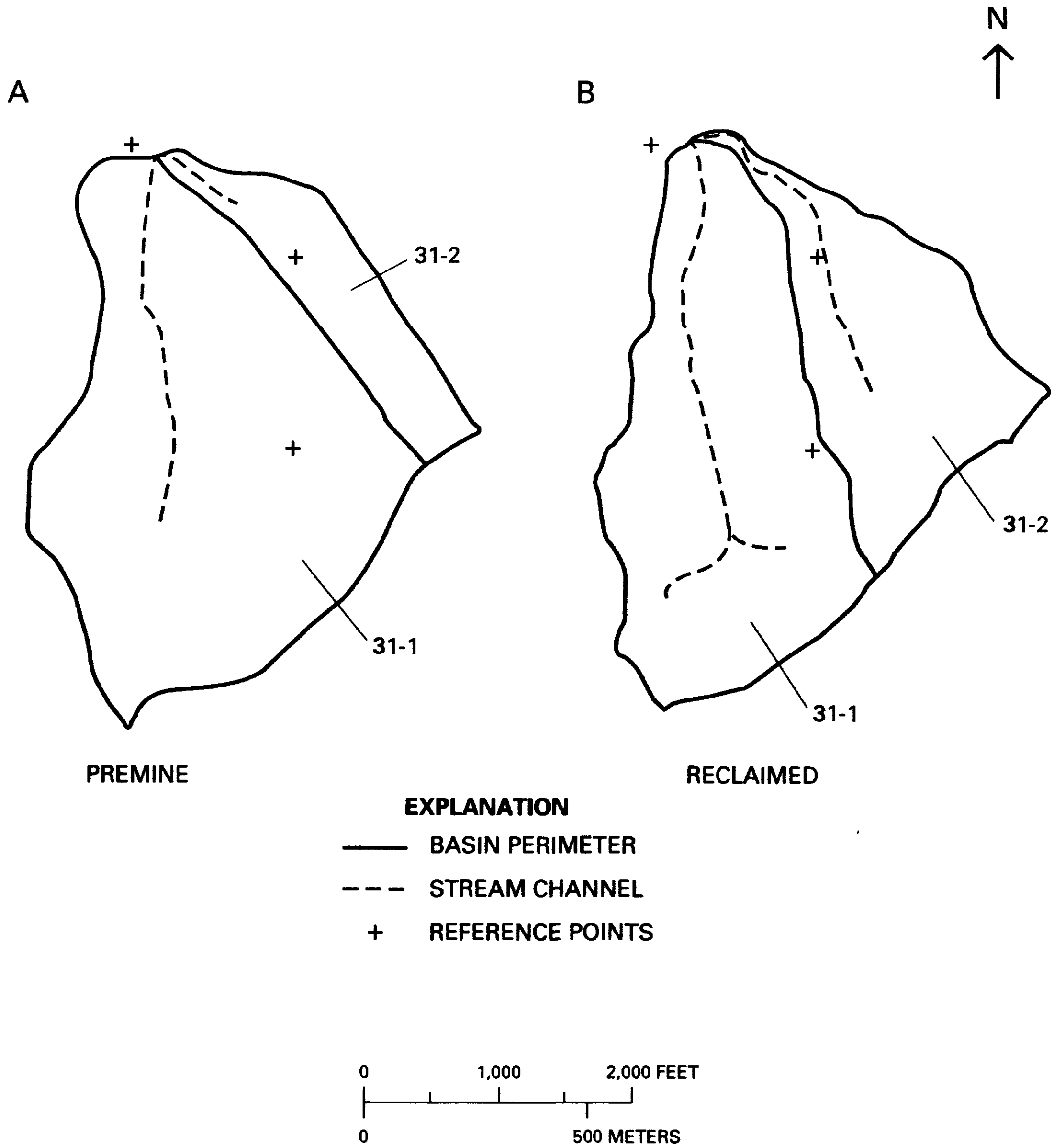

Figure 15.--Planar configurations of *A*, Premine, and *B*, Reclaimed drainage basins 31-1 and 31-2.

203 acres, and the D_d for the combined basins was about 17.5 ft/acre. After mining and reclamation, the combined A_d of both reclaimed basins is about the same as before mining, about 195 acres (table 3); however, two major changes can be seen in the planar view (fig. 15). First, the common drainage-basin divide between the two reclaimed drainage basins has shifted to the southwest decreasing the A_d of basin 31-1 by 27 percent and increasing the A_d of basin 31-2 by 107 percent. Second, the length and number of stream channels in the two basins have changed. Basin 31-1, originally drained by a single, first-order channel, now is drained by two short, first-order channels and a longer, second-order channel. The L_c in basin 31-1 has increased by about 51 percent

by the extension of the original channel and by the addition of two short tributaries. The L_c in basin 31-2 has increased by about 251 percent by the extension of the original channel. The net effect of the changes in A_d and L_c has been to increase the D_d in both basins. The D_d of basin 31-1 has increased by about 105 percent (to about 34.1 ft/acre) and the D_d of basin 31-2 has increased by about 69 percent (to about 37.2 ft/acre). The D_d for the combined basins has increased by about 101 percent (to about 35.2 ft/acre).

The L_c and A_d data for 24 drainage basins were examined to identify general characteristics of D_d. Data were collected from topographic maps of 9 premine, 10 reclaimed, and 5 unmined drainage basins in the study area (table 3). Nine of the 10 reclaimed drainage basins in the study area existed before mining, and data were collected from topographic maps of both the premine and reclaimed time periods. For example, data for basin EBZ-P were collected from a topographic map of basin EBZ before mining (premine), and data for basin EBZ-R were collected from a topographic map of EBZ after reclamation (reclaimed). The tenth reclaimed drainage basin, P30-R, did not exist before reclamation; therefore, no premine data exist for this basin.

Sixteen of the drainage basins had first-order drainage networks and eight of the drainage basins had second-order drainage networks (table 3). Of the nine drainage basins where data existed from both the premine and reclaimed periods, four had changes in drainage-network order after reclamation; three of these were first-order drainage basins that had been reclaimed to second-order drainage basins, and one was a second-order drainage basin that had been reclaimed to a first-order drainage basin.

The range in L_c was a factor of about 2 to 3 for most drainage basins (fig. 16). D_d of most of these drainage basins was between 15 and 60 ft/acre, as indicated by the reference lines of constant D_d in figure 16. In general, the D_d of second-order drainage basins was greater than the D_d of first-order drainage basins for a specific A_d, reflecting a greater L_c in these second-order drainage basins.

The relation between D_d and the stability of valley floors in reclaimed drainage basins is not clear. The distribution of data plotted in figure 16 indicates that, for drainage basins in the study area, the average D_d generally decreases with increasing A_d. However, this relation cannot be used to determine a specific D_d appropriate for a reclaimed drainage basin where many of the controlling variables have been altered. In naturally evolved drainage basins, D_d is affected by geology, geomorphology, pedology, climate, vegetation, stage of development of the drainage network, and hydrology.

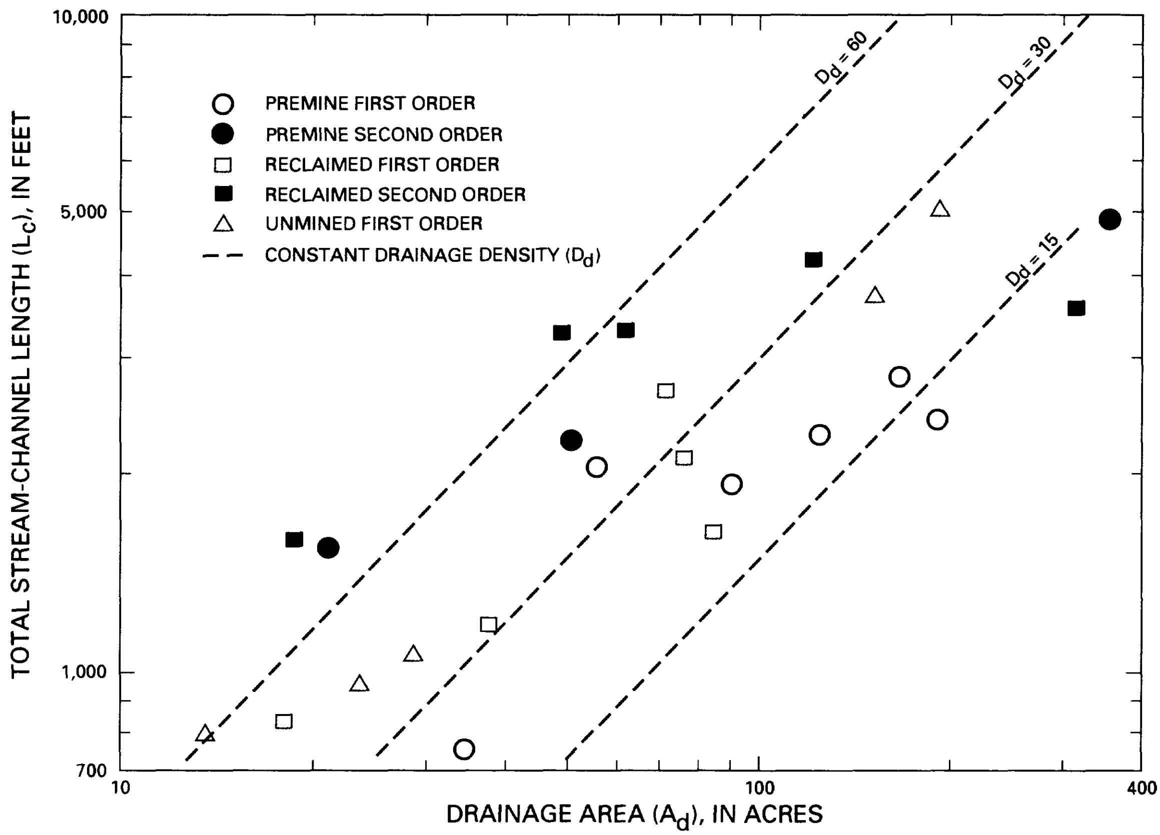

Figure 16.--Relation of total stream-channel length to drainage area of selected first- and second-order drainage networks in premine, reclaimed, and unmined drainage basins.

Conversely, D_d affects streamflow characteristics and sediment yield. Mean annual runoff, flood peaks, and sediment yields are larger in drainage basins that have large D_d than in basins that have small D_d, when the geology, relief, climate, and land use are similar (Schumm, 1977, p. 22). Arbitrarily creating a drainage network with an inappropriate D_d could cause additional erosion and sedimentation problems if the D_d was not adjusted to the new geology, geomorphology, pedology, vegetation, and hydrology of the reclaimed drainage basin. Additional empirical studies are needed to determine appropriate D_d for reclaimed drainage basins.

Reclamation of large areas of surface-mined land has resulted in redistribution of the land mass in some reclaimed drainage basins in northwestern Colorado. Most of the mines included in this study were located on geologic dip slopes. The nature of surface mining and reclamation on a geologic dip slope often results in a net accumulation of spoil material on lower slope areas, and a net removal of spoil material from upper slope areas. This redistribution of spoil material and, therefore, of land mass, often is reflected in the geomorphology of the reclaimed drainage basin.

A hypsometric curve is a graphical representation of land-mass distribution in a drainage basin. Hypsometric curves from a surface-mined drainage basin are shown in figure 17. Elevation and drainage area have been standardized and expressed as percentages so drainage basins of different size can be compared. The curves may be visualized as vertical sections of the drainage basin along the valley floor. The two hypsometric curves from drainage basin 31-1 represent premine and reclaimed land-mass distributions. The premine hypsometric curve generally is concave from the drainage-basin divide to the mouth and is typical of a mature stage of drainage-basin evolution where the location of denudation and sediment production has migrated toward the head of the drainage basin (Schumm, 1956). The step-like drops in the curve probably indicate locally steep reaches of the valley floor, perhaps reaches where there were resistant geologic controls before mining. The hypsometric curve from reclaimed drainage basin 31-1 generally is convex from the drainage-basin divide to the mouth and, in a naturally evolved drainage basin, would be typical of a more youthful stage of drainage-basin evolution. In drainage basins that have convex hypsometric curves, the most rapid rates of denudation and sediment production occur near the middle part of the drainage basin or near the mouth of the drainage basin. Step-like drops and the overall convexity in the hypsometric curve of the reclaimed drainage basin are the result of spoil-material handling and recontouring.

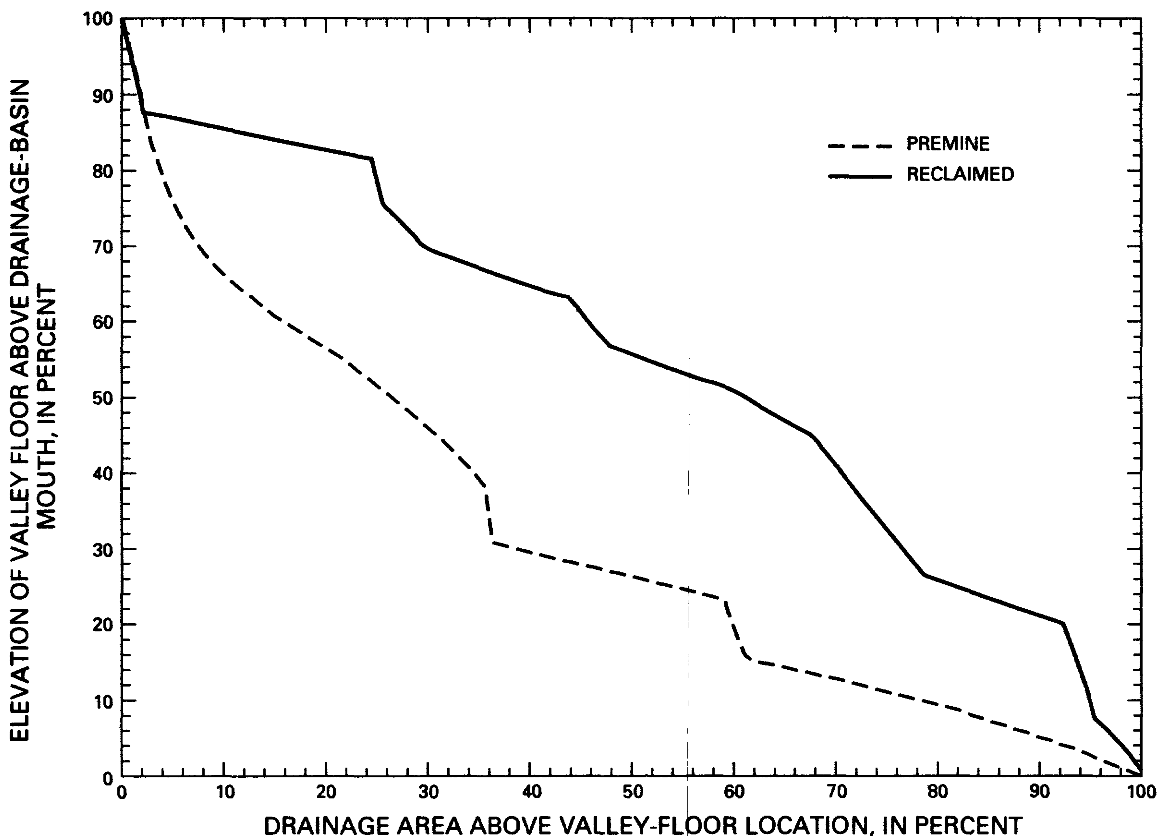

Figure 17.--Standardized hypsometric curves from premine and reclaimed drainage basin 31-1.

Substantial changes between premine and reclaimed hypsometric curves indicate that the distribution of land mass has been altered in many reclaimed drainage basins. In addition to the redistribution of land mass, the zone of highest sediment production may have been relocated within the drainage basin. A high potential for erosion may exist in the middle to lower parts of reclaimed drainage basins where steeper valley and hillslope gradients have been created by spoil recontouring and where large contributing drainage areas exist.

G_v, sometimes referred to as valley slope, is another geomorphic variable that has a substantial effect on the erosion potential of a reclaimed valley floor. Stream-channel gradient (S) is dependent on G_v and sinuosity. The average shear stress, τ_o, affects stream-bed degradation and is directly proportional to S by:

$$\tau_o = \gamma R S, \qquad \text{(DuBoys, 1879)}, \qquad (1)$$

where γ = unit weight of water; and
R = hydraulic radius of flow, the ratio of flow area to wetted perimeter.

Therefore, sediment production and transportation in gullies and degraded stream channels in some reclaimed valley-floor reaches may be partly a function of G_v of the reclaimed drainage basin.

Previous studies have identified a strong inverse relation between G_v and A_d. G_v from consecutive valley-floor reaches of the drainage basins in the study area were determined from the elevation change and horizontal spacing of adjacent contour lines on topographic maps. G_v from the 9 premine, 10 reclaimed, and 5 unmined drainage basins in the study are plotted against A_d in figure 18. The distribution of data reflects the large range of G_v for a specific A_d. A strong inverse relation between G_v and A_d does not exist because most of these drainage basins are located on uniformly dipping geologic structures; as a result, G_v does not change appreciably as A_d increases.

G_v and A_d data from the premine and unmined drainage basins overlap considerably indicating that the unmined drainage basins were similar to the premine drainage basins in terms of G_v and A_d. Data from the premine and reclaimed basins do not overlap as much as do data from the premine and unmined basins, but reclaimed G_v generally was within the range of premine G_v for most surface-mined drainage basins in the study area (fig. 18). However, on a reach-by-reach comparison, some reclaimed G_v seemed to be substantially different from the premine G_v (fig. 19). The premine valley-floor profile of drainage basin 31-1 was slightly concave and relatively uniform for most of its length. The reclaimed valley-floor profile of this drainage basin has a small convexity in the upper part of the basin (near site 311-1), a long concavity in the middle part of the basin (site 311-1 to near site 311-7), and a pronounced convexity in the lower part of the basin (near site 311-7 to site 311-9). The convexity in the lower part of the reclaimed drainage basin resulted from spoil handling and the redistribution of land mass in drainage basin 31-1 (fig. 17). Subtle changes in reclaimed valley-floor profile and increases in local G_v may have increased the erosion potential of some valley-floor reaches, especially where the contributing drainage area is large.

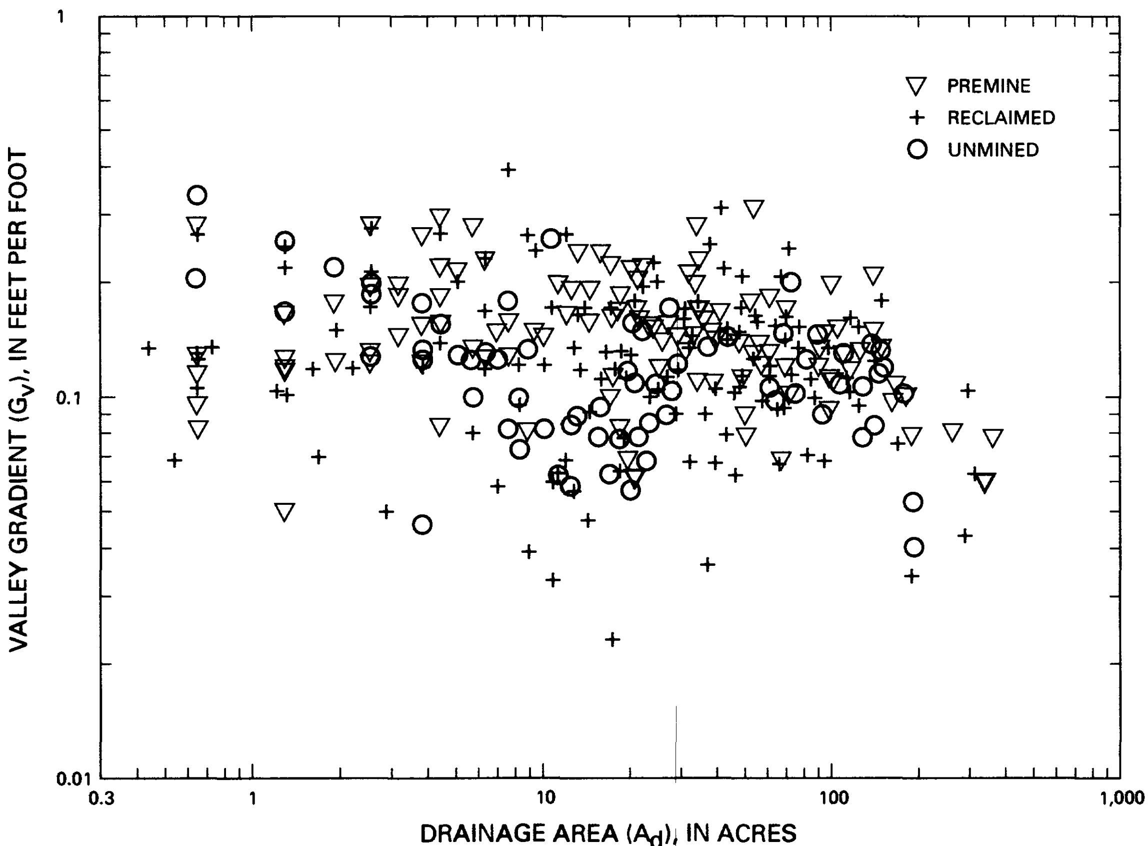

Figure 18.--Relation of valley gradient to drainage area from premine, reclaimed, and unmined drainage basins, using topographic-map data.

The effect of G_v on the erosion potential of the valley floor was further investigated using data collected onsite (table 4). Twenty-seven reclaimed valley-floor reaches and seven unmined valley-floor reaches were surveyed, longitudinal profiles were plotted, and local G_v were determined. The large variance in G_v relative to A_d, shown in figure 20, indicates a small correlation between these two geomorphic variables. Some of the overall variance in data from reclaimed valley-floor reaches is accounted for when the data are categorized on the basis of valley-floor stability; data from the unstable reclaimed reaches tended to be clustered in the upper part of the plot. All of the reclaimed valley-floor reaches that had A_d less than about 13 acres were stable. By contrast, most reclaimed valley-floor reaches that had A_d greater than about 13 acres and G_v greater than about 0.06 ft/ft were unstable.

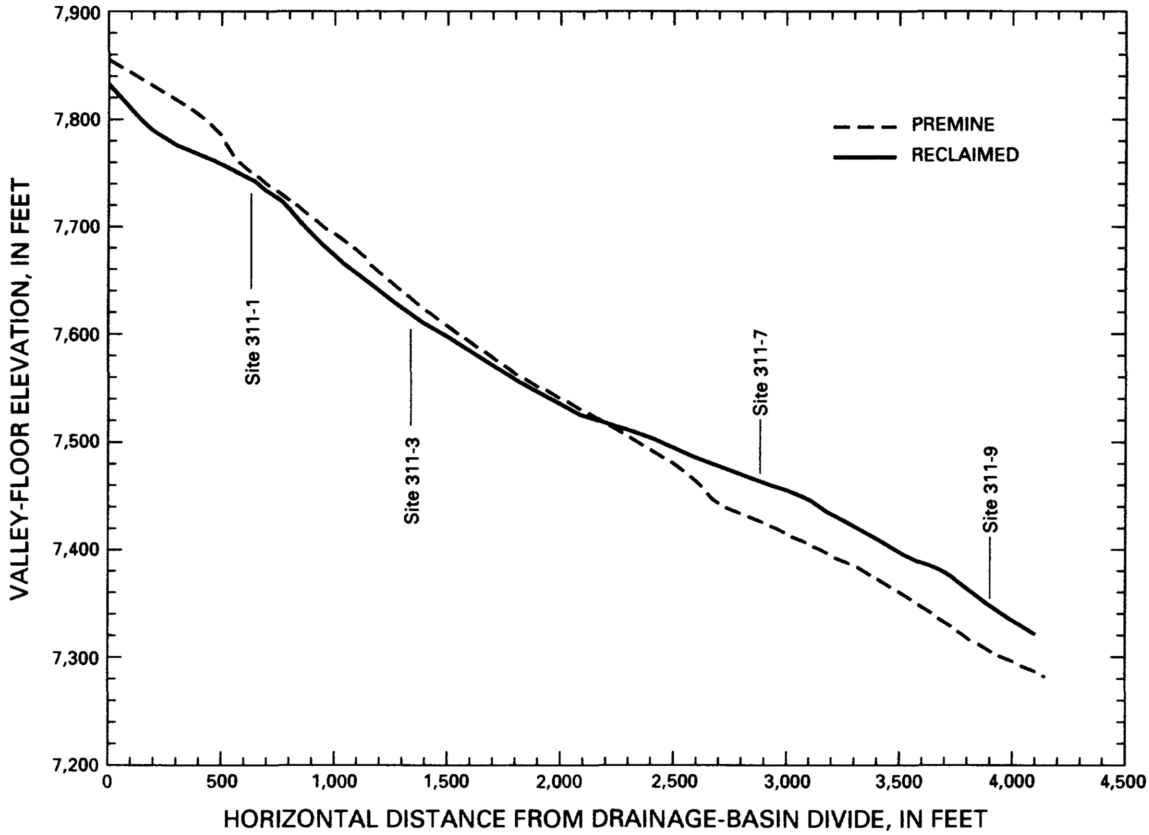

Figure 19.--Valley-floor profiles from premine and reclaimed drainage basin 31-1.

Data from unmined valley-floor reaches are included in figure 20 for comparison. It was assumed that geomorphic conditions in the nearby unmined drainage basins are representative of geomorphic conditions that existed before mining in what are now the reclaimed drainage basins. Most of the unmined valley-floor reaches were stable, but two were healing after an earlier period of instability. Data from the the unstable reclaimed valley-floor reaches plot with data from the unmined valley-floor reaches. Most stable reclaimed reaches have smaller values of G_v than do unmined reaches for similar A_d. Although the values of G_v and A_d of many reclaimed valley-floor reaches are similar to the values of G_v and A_d of unmined valley-floor reaches (fig. 20), many of these reclaimed valley-floor reaches were less stable than the nearby unmined valley-floor reaches.

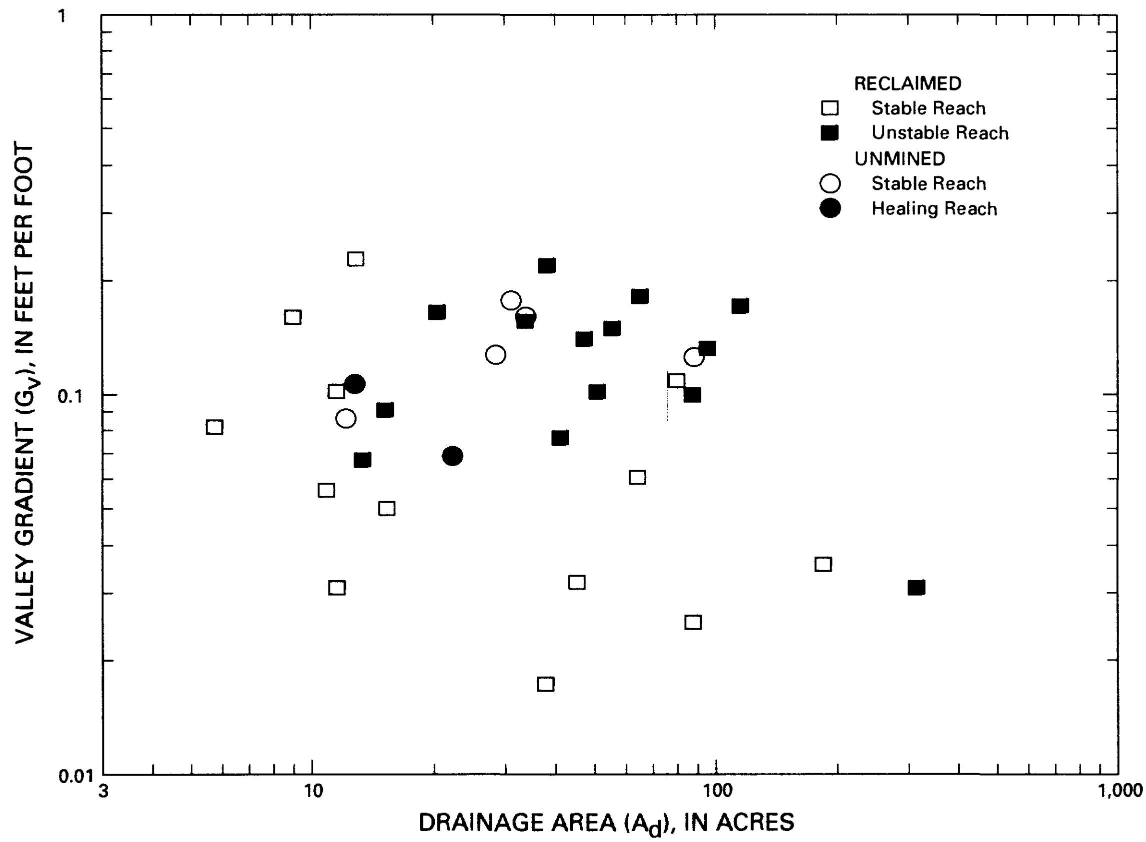

Figure 20.--Relation of valley gradient to drainage area from surveyed valley-floor reaches (from Elliott, 1989).

The relation between G_v and A_d and the erosional stability of surveyed reclaimed valley floors can be used to assess the erosion potential of other mapped valley-floor reaches. Map-derived G_v and A_d data from the reclaimed drainage basins shown in figure 18 were compared with survey-derived G_v and A_d data (fig. 21). Many of the mapped reclaimed valley-floor reaches plotted with the surveyed unstable reaches. This indicates that many unsurveyed valley-floor reaches in reclaimed drainage basins are potentially unstable because G_v is steep relative to A_d. Many of these same reaches may have been stable at comparable G_v before mining and reclamation because geologic controls, vegetation cover, and surface runoff were in a natural state.

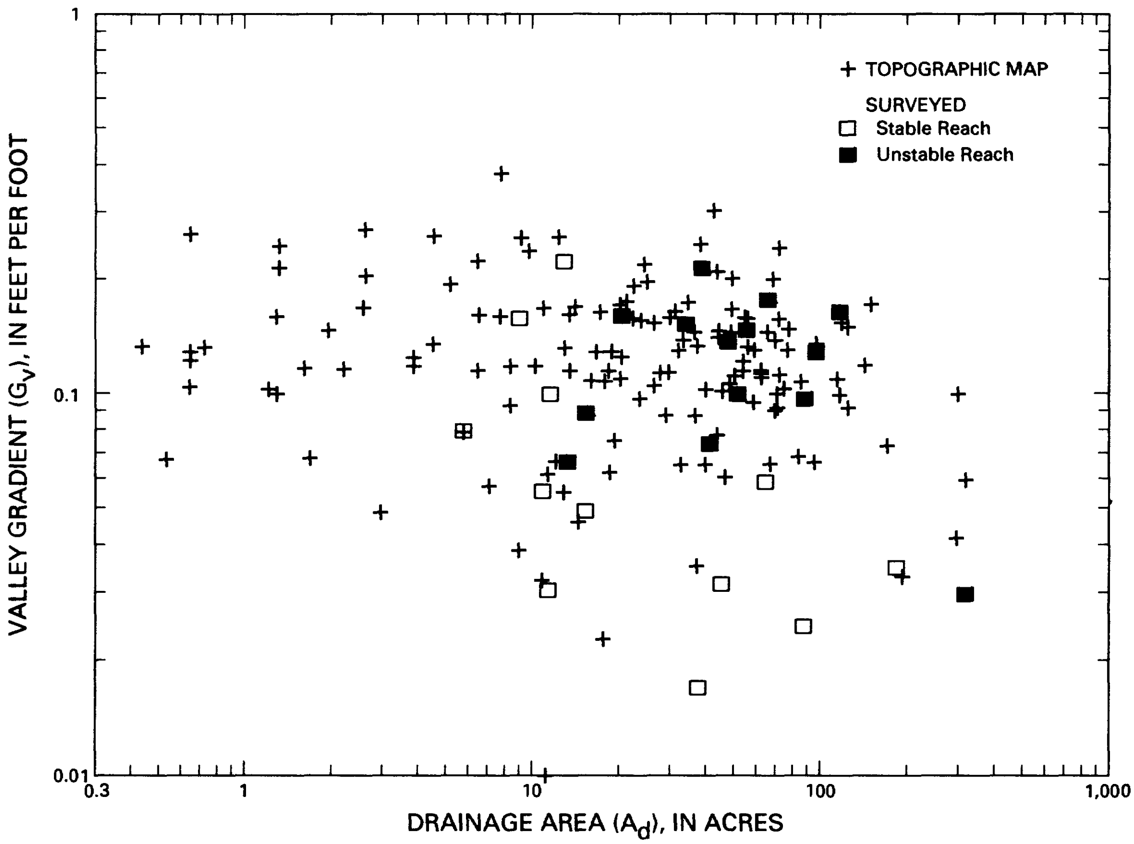

Figure 21.--Relation of valley gradient to drainage area from reclaimed drainage basins showing comparison of topographic-map and survey data.

Begin and Schumm (1979) studied gully erosion and instability of alluvial valley floors. They investigated the effect of A_d and G_v on the τ_o exerted by flow on the valley floor. In equation 1, τ_o is the tractive force per unit surface area and is a function of γ, R, and S (DuBoys, 1879). S can be approximated by G_v when sinuosity is low. For wide, shallow flows, which may occur on an initially ungullied valley floor, R can be approximated by flow depth (D). Therefore, equation 1 can be approximated by:

$$\tau_o = \gamma \, D \, G_v \; . \tag{2}$$

The cross-sectional area, flow width (W), D, and mean flow velocity have been empirically related to discharge (Q) in many hydraulic geometry studies (Leopold and others, 1964). Similarly, regional studies have related Q to drainage-basin characteristics, most commonly A_d, by power functions (Burkham, 1966; Riggs, 1973). Using these empirical relations, Begin and Schumm (1979) proposed that τ_o, acting on a valley floor, could be related to A_d and G_v by a shear-stress indicator (τ_i):

$$\tau_i = c\, A_d^{rf}\, G_v\ , \tag{3}$$

where coefficients c and rf are determined by empirical relations between D and Q and between Q and A_d. In equation 2, γ is 1. The τ_o becomes a shear-stress indicator τ_i because many assumptions were made about the relations between hydraulic and geomorphic variables. Begin and Schumm (1979) suggested that the range of rf in equation 3 was about 0.2 to about 0.4, based on empirically determined exponents for hydraulic geometry and based on the relation between Q and A_d. Because of the small value of rf, τ_i is much more sensitive to changes in G_v than to changes in A_d.

The data in figure 20 have a large variability, and an empirical relation for τ_o cannot be derived for reclaimed valley floors. However, the general effect of A_d and G_v on valley-floor stability can be represented with the AGI. AGI is the product of A_d and G_v and is not dependent on empirically determined coefficients and exponents. The units of AGI are the units of A_d--in this report, acres.

The AGI is a geomorphic index of the potential total stream power (Ω) acting on a valley-floor reach. Stream power is the amount of energy input to a stream reach by the transporting fluid. Ω is defined as the product of the fluid mass density (ρ), gravitational acceleration (g), Q, and S (Bagnold, 1966):

$$\Omega = \rho\ g\ Q\ S\ . \tag{4}$$

If Q is strongly correlated with A_d and if S is equivalent to G_v, then Ω may be approximated by:

$$\Omega = A_d^{\,j}\ G_v\ , \tag{5}$$

where j is a coefficient determined by the empirical relation between Q and A_d. The value of j is close to 1.0 for many drainage basins (Burkham, 1966; Elliott and Cartier, 1986) so the right side of equation 5 can be approximated by AGI, and Ω becomes a geomorphic index of the potential total stream power (Ω_i) because of the assumptions made about the relation between Q and A_d:

$$\Omega_i = AGI\ . \tag{6}$$

Surveyed G_v and A_d data from stable reclaimed and unstable reclaimed valley-floor reaches overlap to some degree (fig. 20). However, a t-test of group means indicated there was a significant difference between the AGI of stable reclaimed valley-floor reaches and unstable reclaimed valley-floor reaches (P = 0.0034, 95-percent level). The mean AGI of stable reclaimed reaches was about 2.4 acres, and the mean AGI of unstable reclaimed reaches was about 7.6 acres.

Two reference lines of constant AGI (1 and 10) are superimposed on a plot of A_d and G_v from surveyed reclaimed valley floors (fig. 22). Two general conclusions can be made for reclaimed valley floors in this study: (1) The lower limit of AGI for unstable valley-floor reaches is about 1, and (2) the upper limit of AGI for stable valley-floor reaches is about 10. Additional surveys of valley floors in reclaimed drainage basins might identify stable reclaimed valley-floor reaches with AGI greater than 10.

The AGI is computed easily for valley-floor reaches of topographically mapped drainage basins using planimetered A_d and using G_v determined by adjacent contour lines. By computing AGI for successive intervals along the length of a drainage basin, down-valley AGI trends may be plotted (fig. 23).

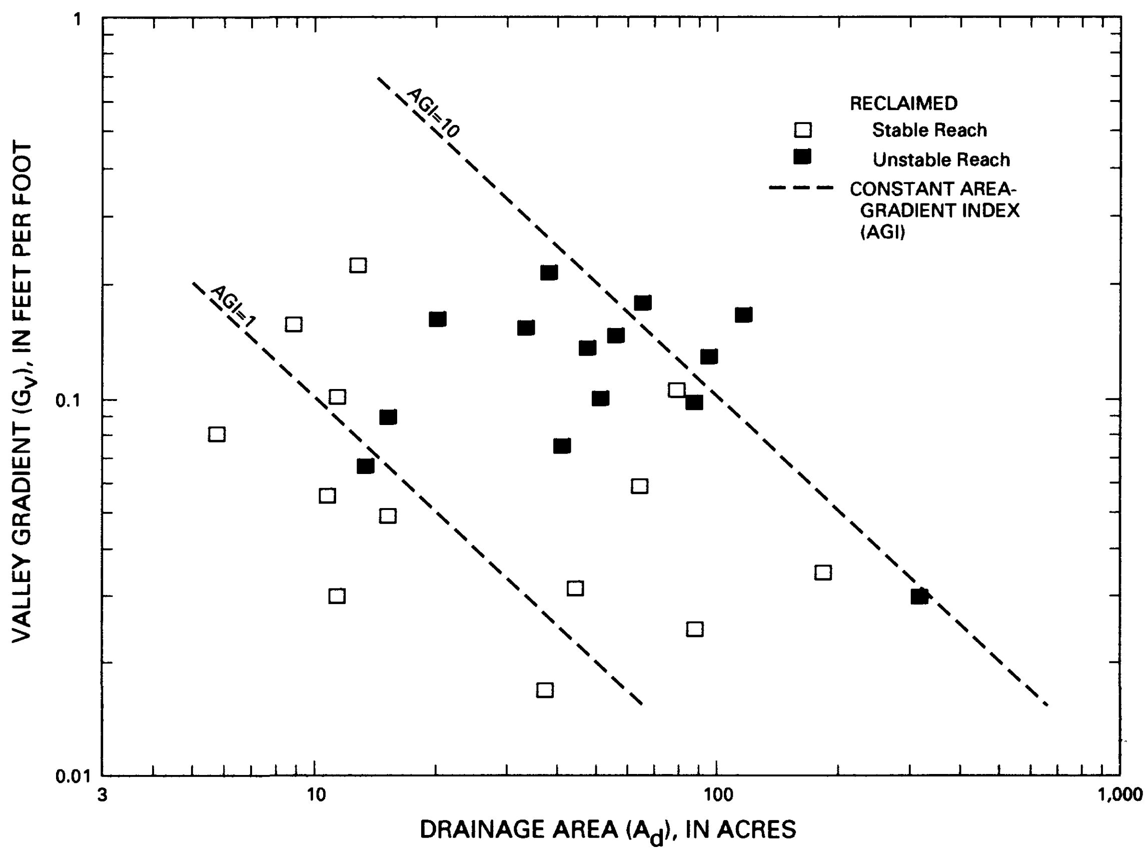

Figure 22.--Relation of valley gradient to drainage area from surveyed valley-floor reaches with lines of constant area-gradient index.

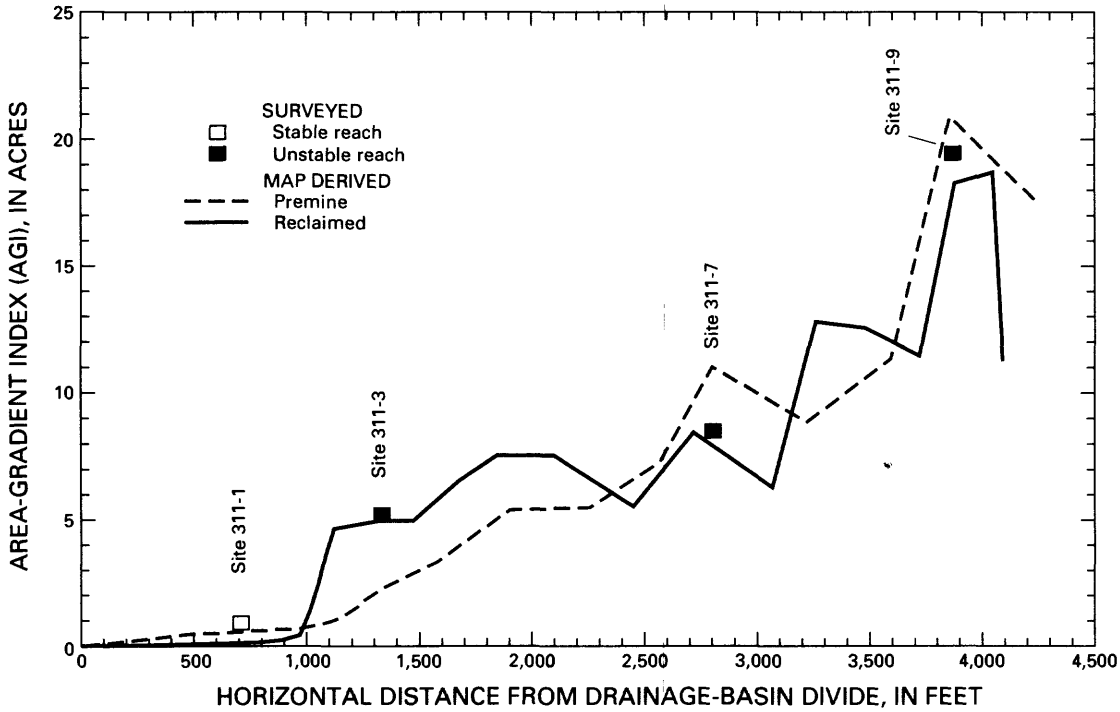

Figure 23.--Down-valley area-gradient-index trends from premine and reclaimed drainage basin 31-1.

There is an increasing, down-valley trend in AGI for both the premine and reclaimed drainage basin 31-1. AGI for most of the other drainage basins in the study increased down valley also. The increasing, down-valley trend in AGI is a result of A_d increasing at a faster rate than G_v decreases down valley. Most of the drainage basins in the study were located on dip slopes, and G_v did not decrease substantially down valley (fig. 18).

The AGI for premine drainage basin 31-1 and reclaimed drainage basin 31-1 increases to more than 10 in the lower one-third of both drainage basins (fig. 23). Sharp increases and decreases in the curves are caused by abrupt increases and decreases in local G_v. For the curve representing premine AGI, two peaks at about 2,800 and 3,800 ft from the drainage-basin divide may indicate steeper, bedrock-controlled valley-floor reaches. Peaks in the curve representing reclaimed AGI probably are a result of locally steepened G_v produced by variations in spoil recontouring.

The AGI from four surveyed valley-floor reaches of reclaimed drainage basin 31-1 are superimposed on the map-generated AGI-trend curve (fig. 23). Three of the reclaimed reaches were unstable (eroding) and one reclaimed reach was stable. The reclaimed valley-floor reach surveyed at site 311-1 was stable; the G_v was 0.102 ft/ft, but the A_d was only 11.5 acres; therefore, AGI was 1.2 acres (table 4). Reclaimed valley-floor reaches at sites 311-3, 311-7, and 311-9 were gullied, and AGI's for these reaches were 5.3, 8.7, and 20 acres. AGI's from the surveyed reclaimed reaches did not always plot directly on the map-generated AGI-trend line (fig. 23) because of the comparatively poorer accuracy of the map-generated G_v data.

The upper limit of the AGI of stable reclaimed valley floors in this study was about 10 (fig. 22). The AGI of the upper two-thirds of reclaimed drainage basin 31-1 was less than 10 (fig. 23), but an onsite inspection revealed that much of the valley floor in this part of the drainage basin was gullied. Valley-floor reaches from other reclaimed drainage basins also had AGI less than about 10, but they were not gullied. AGI may give some indication of the erosion potential for a reclaimed valley-floor reach; however, a better assessment of reclaimed valley-floor stability can be made when an additional geomorphic variable is included with AGI.

Valley-floor width W_v is another geomorphic variable that may affect the erosional stability of reclaimed valley floors. The valley floor is a relatively flat area where surface runoff and unsaturated-zone water from the adjacent valley-side hillslopes collect. The lateral limits of the valley floor are determined by the morphology of the adjacent hillslopes (fig. 24). The valley floor in a small drainage basin may be analogous to the flood plain in a larger drainage basin; the valley floor, or flood plain, is an area where erosive forces (total stream power) of large streamflows are dissipated. A narrow valley floor, or flood plain, will tend to concentrate flood flows, increasing flow depth, flow velocity, unit stream power, and the likelihood of some type of erosion. Although floods that inundate the valley floor of a small drainage basin may occur infrequently, a narrow valley floor increases the potential for gully erosion or channel degradation by concentrating surface runoff (Harvey and others, 1985) and unsaturated-zone water.

Valley-floor morphology in a naturally evolving drainage basin primarily is determined by local geology, geomorphic processes acting on adjacent valley-side hillslopes, and fluvial processes acting on the valley floor. W_v, in naturally evolving drainage basins, often is related to A_d; however, W_v of reclaimed drainage basins in this study was uncorrelated with A_d. This may be because reclaimed-valley morphology often is an artifact of spoil-material handling during reclamation. W_v of reclaimed drainage basins ranged from about 20 to 65 ft (table 4). Many unstable valley-floor reaches had a narrower W_v for a specific A_d than did stable valley-floor reaches, but t-tests of the mean of W_v indicated that the difference between the stable reclaimed reaches and unstable reclaimed reaches was not statistically significant (95-percent level).

The importance of W_v becomes more apparent when W_v is evaluated with the two previously discussed geomorphic variables, A_d and G_v. Bradley (1980) determined that valley-floor gully initiation in northeastern Colorado drainage basins was affected by all three geomorphic variables; A_d, G_v, and W_v.

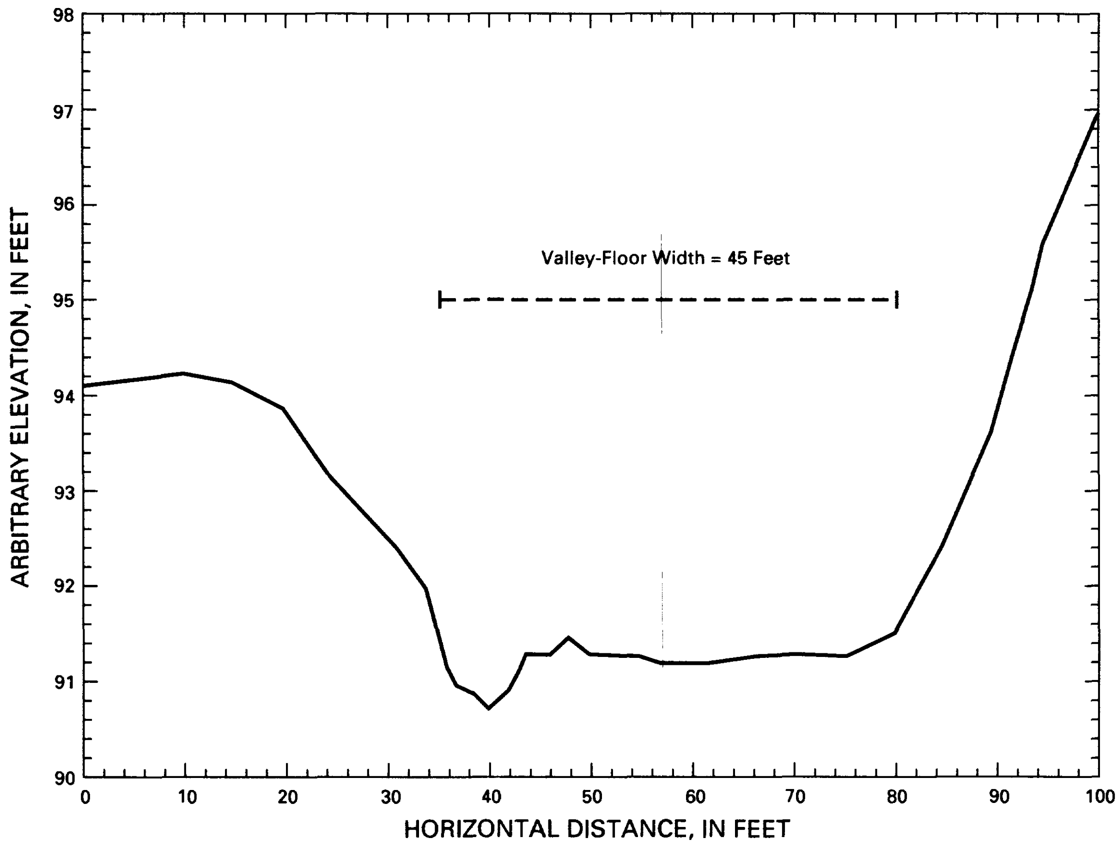

Figure 24.--Transverse valley-floor profile from a reclaimed drainage basin, site S70-5.

The AGI, the product of A_d and G_v, is a geomorphic index of the potential total stream power acting on a valley-floor reach (eq. 6). AGI also is a scaling factor because, for drainage basins in the study area with relatively constant G_v, AGI generally increases with A_d.

W_v data from 13 stable reclaimed valley-floor reaches, 14 unstable reclaimed valley-floor reaches, and 7 stable and healing unmined valley-floor reaches were plotted against AGI (fig. 25). There are no obvious linear relations between W_v and AGI, but there are data clusters from the stable reclaimed and unstable reclaimed reaches. Data from stable reclaimed reaches tend to plot in the upper and left parts of the figure, whereas data from unstable reclaimed reaches tend to plot in the lower and right parts of the figure. Data from the two reclaimed groups overlap slightly, but the overlap is much less than when G_v was plotted against A_d (fig. 22). Data from three of the stable unmined valley-floor reaches plot with data from stable reclaimed reaches (fig. 25). Data from the two healing unmined valley-floor reaches plot with data from unstable reclaimed reaches. These healing unmined reaches had indications of previous instability, but were healing at the time they were surveyed (1987).

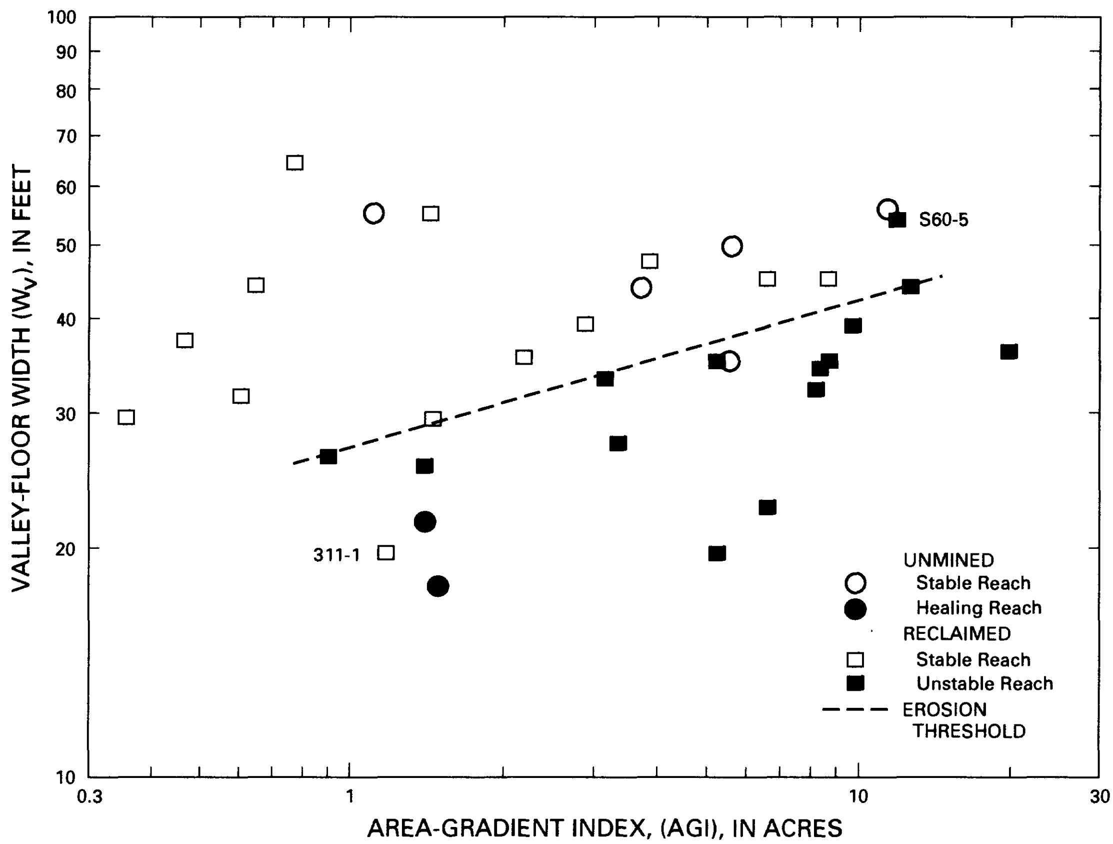

Figure 25.--Relation of valley-floor width to area-gradient index from surveyed valley-floor reaches (from Elliott, 1989).

Valley-Erosion Threshold

The clustering of W_v and AGI data (fig. 25) may define a threshold zone between stable and unstable reclaimed valley floors for different combinations of W_v and AGI. A t-test of group means indicated that there was no signifi cant difference between W_v of stable reclaimed valley-floor reaches and unsta ble reclaimed valley-floor reaches (P = 0.10, 95-percent level). However, an analysis of covariance indicated there was a significant difference in the relation of W_v and AGI between stable and unstable reclaimed valley-floor reaches. Stable reclaimed valley-floor reaches tend to have wider W_v than unstable reclaimed valley-floor reaches for the same AGI (fig. 25).

A threshold line on figure 25 separates most of the stable reclaimed valley-floor reaches from most of the unstable reclaimed valley-floor reaches. Valley-floor reaches plotting above the threshold line tend to be stable, whereas reaches plotting below the threshold line tend to be unstable. This line represents the valley-erosion threshold for reclaimed drainage basins in the study area and is represented mathematically as:

$$W_v = 28\ AGI^{0.19} \quad . \tag{7}$$

The valley-erosion threshold was graphically fitted in figure 25 and does not represent a statistically defined discriminant-function line.

Two reclaimed valley-floor reaches do not plot with groups delineated by the valley-erosion threshold (fig. 25). Site 311-1 (AGI = 1.2, W_v = 20) was classified as stable, but it plots with unstable valley-floor reaches. The valley floor at this site had several large, discontinuous rills, but no gully or incised channel. It is possible that the valley floor at site 311-1 was unstable, but that the characteristics used to classify unstable sites (presence of a gully or degraded channel) had not yet developed. Site S60-5 (AGI = 12, W_v = 55) was classified as unstable, but it plots with stable valley-floor reaches (fig. 25). When this site was surveyed in 1987, the channel was incised, apparently because it was inadvertently confined to an area of the valley floor by mechanical channelization. Re-inspection of site S60-5 in 1988 indicated that the channel may be stabilizing.

Bradley (1980) discriminated between ungullied and gullied valley-floor reaches in the Chalk Bluffs area of northeastern Colorado using A_d, G_v, and W_v. He described the erosion threshold identified in his study in terms of geomorphic (unit) stream power (ω). A similar approach was used with the data from reclaimed drainage basins in northwestern Colorado.

The Ω_i (eq. 6), can be modified to an index of potential unit stream power (ω_i) by dividing by W or W_v. ω is the total stream power (Ω) per unit bed area, or W, and is defined by Bagnold (1966):

$$\omega = \frac{\Omega}{W} \quad . \tag{8}$$

On a relatively flat, initially ungullied or unchanneled valley floor, W may be approximated by W_v for some large Q. Because A_d is a surrogate for Q, dividing equation 5 by W_v gives a geomorphic index of potential unit stream power (ω_i):

$$\omega_i = c\ A_d^{\ j}\ G_v\ W_v^{\ -1} \ ; \tag{9}$$

where c and j are coefficients determined by the empirical relations between A_d and G_v, and between Q and A_d.

A valley-erosion index (VEI) can be derived from equation 9 by substituting the AGI for A_d and G_v:

$$VEI = c'\ AGI^k\ W_v^{\ -1} \ ; \tag{10}$$

where c' and k are empirically determined coefficients that represent the relations between W_v and AGI, between A_d and G_v, and between Q and A_d.

The valley-erosion threshold (eq. 7) was defined by the clustering of data from stable and unstable valley-floor reaches and the relation between W_v and the AGI. Substituting the coefficients from equation 7 into equation 10 defines the threshold value of the valley-erosion index (VEI_t):

$$VEI_t = 28\ AGI^{0.19}\ W_v^{-1}\ . \qquad (11)$$

By definition, the value of VEI_t equals 1.0.

Stable valley-floor reaches that plot near the valley-erosion threshold (fig. 25) may be potentially unstable and could become unstable and gullied if, for example, annual runoff increased substantially during a climatic fluctuation, or if a disturbance on the valley floor initiated channel incision. Conversely, unstable reaches plotting near the valley-erosion threshold could begin to stabilize if, for example, annual runoff decreased as vegetation cover in the drainage basin matured and evapotranspiration increased.

The relative stability or instability of the reclaimed valley-floor reaches in this study (fig. 25) can be quantified based on the distance of each point from the valley-erosion threshold line. The VEI is calculated for each valley-floor reach using the reach AGI and W_v (table 4), and the coefficient and exponents of the VEI_t (eq. 11). Because $VEI_t = 1.0$, VEI calculated for a specific valley-floor reach gives a quantitative assessment of valley-floor instability (or erosion potential) relative to the valley-erosion threshold. The distance a point plots from the threshold line is described in terms of the VEI.

Lines of constant relative VEI are superimposed on the plot of W_v and AGI (fig. 26). Most of the unstable valley-floor reaches have VEI from 1.0 to about 1.3 times the value of the VEI_t. However, for two unstable reaches, the VEI is almost twice as large as VEI_t. Most of the stable reclaimed valley-floor reaches have VEI from about 0.7 to 1.0 times VEI_t.

Determination of VEI enables a quantitative assessment of the erosion potential of reclaimed valley floors when three geomorphic variables are known. However, these VEI are based on geomorphic variables and can give only a simplistic approximation of the hydraulic conditions that affect erosion and valley-floor stability. Additionally, the VEI for an individual valley-floor reach is dependent on the coefficient and exponents of the VEI_t (eq. 11). The coefficient, exponents, linearity, and limits of the valley-erosion threshold were empirically determined by the distribution of stable and unstable data points plotted in figure 25. Inclusion of new data from other reclaimed valley-floor reaches could change the position of the valley-erosion threshold. Also, the valley-erosion threshold may shift with time as the stability of the studied reaches changes in response to evolving geomorphic, pedologic, vegetation, and hydrologic conditions. Therefore, equation 11 needs to be considered as defining a zone or an approximation of the threshold between stable and unstable reclaimed valley-floor reaches observed in the study area.

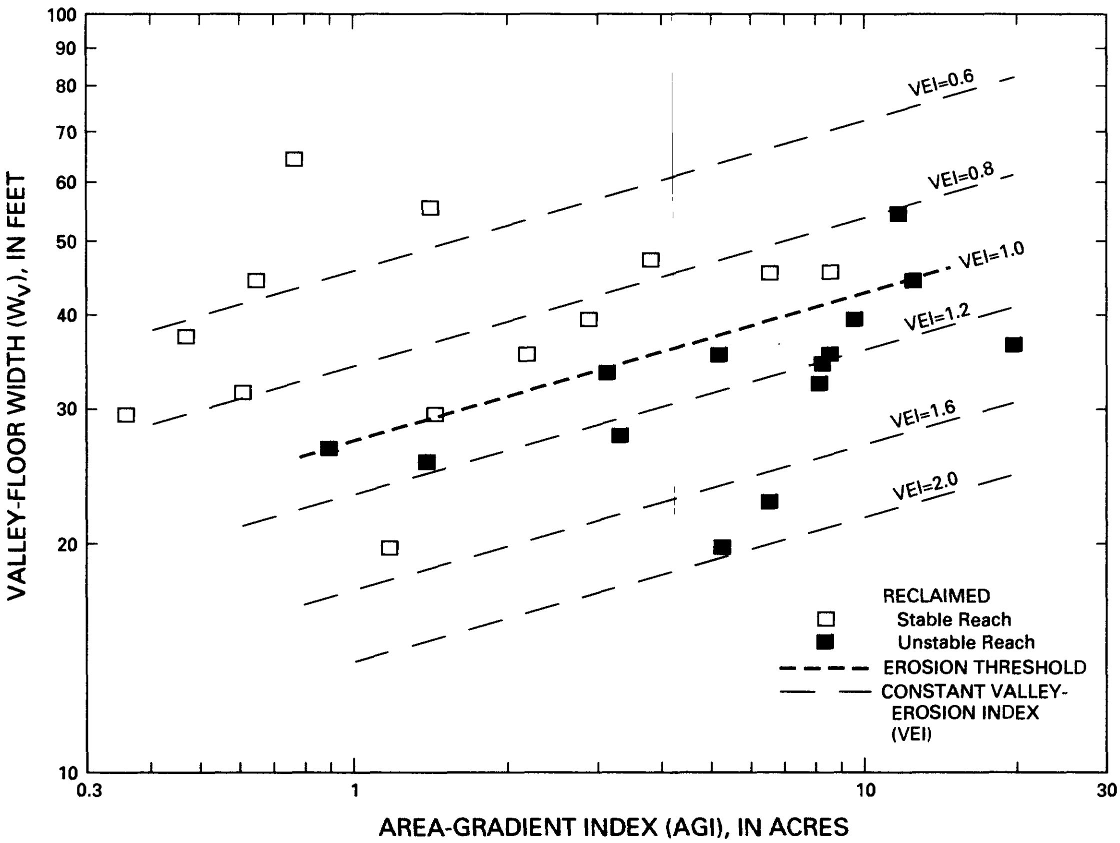

Figure 26.--Relation of valley-floor width to area-gradient index with lines of constant valley-erosion index (from Elliott, 1989).

SUMMARY

Recurrent rill erosion and gully erosion have been observed on some reclaimed surface coal mines in northwestern Colorado. Surface mining and reclamation activities result in substantial changes in geology, geomorphology, pedology, vegetation, and hydrology. Some of the erosion observed on reclaimed lands may be due to replacement of resistant geologic materials with unconsolidated spoil material, changes in topsoil properties and vegetation type, or increased surface runoff; however, much of this erosion may be caused or exacerbated by an imbalance of geomorphic conditions created during reclamation activities.

Landforms are modified by erosion, a process common to all land surfaces. Over time, many landforms may become stable or approach a relative equilibrium with the controlling geologic, climatic, vegetation, and hydrologic conditions of the area. Erosion rates can accelerate if there are changes in the controlling variables, such as tectonism, climate, vegetation, or land use. Surface mining and reclamation of large areas of land have caused changes in some of the variables that control erosion rates. Therefore, the equilibrium geomorphic conditions (landforms) for reclaimed surface-mined lands may be substantially different than the equilibrium geomorphic conditions that existed before mining. Reclaiming surface-mined land to the approximate original contours may be inappropriate, depending on the nature and extent of changes resulting from surface mining.

One means of decreasing the erosion potential of reclaimed surface-mined lands is to identify and create equilibrium geomorphic conditions that can exist with the postmining controlling variables. The approximate equilibrium conditions for reclaimed surface-mined lands in northwestern Colorado can be identified empirically.

Two important types of erosion were observed at reclaimed surface coal mines in northwestern Colorado--rills and gullies. Rills are small, linear erosion features that cause topsoil loss and impede vegetation growth. Gullies are larger, unstable channels that cause substantial topsoil loss and spoil-material mobilization. Erosion in the study area was associated with two distinct geomorphic areas: (1) Rills, and occasionally gullies, were observed on hillslopes; and (2) gullies, or unstable stream channels, were observed on valley floors.

Erosion of reclaimed hillslopes was studied at the Trapper, Hayden Gulch, Grassy Gap, Seneca II, and Edna Mines. Data were collected from 10 reclaimed hillslopes and from 4 nearby unmined hillslopes for comparison. Reclaimed hillslopes selected for study had morphology, aspect, and vegetation cover typical of the hillslopes elsewhere at the mines. Unmined hillslopes selected for study were geographically similar to reclaimed hillslopes.

Rill erosion and gully erosion were more common on the reclaimed hillslopes than on the unmined hillslopes included in the study. Reclaimed hillslopes and unmined hillslopes had similar elevation, hillslope length, and hillslope gradient; however, reclaimed hillslopes had greater topsoil bulk densities, lower topsoil-infiltration rates, and less woody vegetation than the unmined hillslopes. Topsoil in reclaimed areas was removed from the original location, stored in stockpiles, and reapplied by heavy machinery. These activities tended to mix soil horizons and to compact the structure of the soil. Vegetation in reclaimed areas was almost entirely perennial grasses and forbs; woody species composed a small percentage of the vegetation cover. Soils and vegetation on the unmined hillslopes were diverse and varied with elevation, geologic parent material, and microclimate.

There were differences between reclaimed hillslope profiles and unmined hillslope profiles. Several reclaimed hillslopes had constant or increasingly steep (convex) hillslope gradients from the upper hillslope segment down to the lower hillslope segment. By comparison, unmined hillslopes usually became less steep (concave) from the upper segment to the lower segment. Rills on reclaimed hillslopes generally occurred on the mid-hillslope to lower hillslope segments and on segments of steep hillslope gradient. Rill densities on reclaimed hillslopes were positively correlated with the hillslope-length, hillslope-gradient product and were inversely correlated with the age of the hillslope since reclamation.

Post-reclamation disturbances of the topsoil and vegetation cover (plowing, reseeding, contour furrowing, grading) also were associated with initiation of some rill erosion that, occasionally, extended from the disturbed area into adjacent reclaimed areas. Gullies were observed on some reclaimed hillslopes and generally developed on steep or convex hillslope segments and below hollows that may have functioned as moisture-collection areas. No rills or gullies were observed on the four unmined hillslope study areas that were used as control sites. Erosion on the four unmined hillslopes was mostly isolated sheet erosion.

Data from infiltration measurements on hillslopes varied greatly, were limited areally, and, therefore, were not useful in multiple-regression analyses of rill erosion. However, t-tests and a plot of infiltration rate compared to topsoil bulk density indicated that, as a group, the reclaimed hillslopes had lower topsoil-infiltration rates, lower topsoil porosity values, and higher topsoil bulk-density values than the unmined hillslopes. The addition of vegetation data to the analysis also did not significantly decrease the variance of rill density. It is possible that the range of vegetation-cover density was too small to have statistical significance.

Multiple-regression models of rill density were not good predictive tools for hillslope erosion. Analyses of rill erosion on reclaimed hillslopes was imprecise because many important factors that affect hillslope erosion were difficult to quantify or had large variance. The principal variables affecting rill erosion on reclaimed hillslopes seem to be hillslope length, hillslope gradient, and age since reclamation; however, differences in vegetation type and vegetation-cover density, topsoil physical properties, topsoil-infiltration rates, reclamation history, and post-reclamation surface manipulation also affect rill erosion.

Erosion of reclaimed valley floors was studied at the Trapper, Hayden Gulch, Seneca II, and CYCC Mines. Data were collected from 27 reclaimed valley-floor reaches in 10 reclaimed drainage basins. Data also were collected from seven unmined valley-floor reaches in nearby unmined drainage basins for comparison. Valley-floor reaches selected for study represented a wide range of geomorphic conditions in the study area. Reclaimed drainage basins in the study area had drainage-basin areas that ranged from 17.9 to 320 acres, and unmined drainage basins had drainage-basin areas that ranged from 13.4 to 195 acres. All drainage basins in the study had either first- or second-order drainage networks.

Surface mining and reclamation activities have altered several variables that affect the erosional stability of reclaimed valley floors. Changes in topsoil properties and vegetation cover may have increased the surface runoff from reclaimed drainage basins. The valleys of reclaimed drainage basins were re-created from the replaced, crushed spoil material and had no geologic controls. The transverse morphology of many of these reclaimed valleys commonly was narrow and v-shaped, depending on the profile of the adjacent valley-side hillslopes. Gully erosion and unstable channels were more common on reclaimed valley floors than on unmined valley floors. Gully erosion resulted from an excess of erosive forces compared to resistant forces.

Most stable, or ungullied, reclaimed valley-floor reaches could be distinguished from unstable, or gullied, reclaimed valley-floor reaches on the basis of three geomorphic variables: Drainage area (A_d), valley gradient (G_v), and valley-floor width (W_v). A_d often is used as an index of runoff quantity from a drainage basin when streamflow data are not available. G_v is used as a substitute for the energy slope of a valley floor. W_v affects the concentration or dispersion of surface runoff and, possibly, unsaturated-zone water.

The product of A_d and G_v is the area-gradient index (AGI), a geomorphic index of the potential total stream power acting on a valley-floor reach. The relation between valley-floor width (W_v) and AGI, and clustering of data from stable and unstable valley-floor reaches defined the valley-erosion threshold for reclaimed drainage basins in the study area. Reclaimed valley-floor reaches that had W_v narrower than this threshold were more likely to be gul lied than reclaimed valley-floor reaches that had W_v wider than the threshold. The relation between W_v and AGI explains more of the variance in the data than does the relation between G_v and A_d because a third geomorphic variable is included.

The relative stability or instability of the reclaimed valley-floor reaches in this study can be quantified based on the numerical distance of each point from the valley-erosion threshold. A valley-erosion index (VEI) was calculated for each valley-floor reach using the reach AGI and W_v and the coefficient and exponents of the valley-erosion threshold. The threshold value of the valley-erosion index (VEI_t) has a value of 1.0. Most of the unstable valley-floor reaches had VEI from 1.0 to about 2.0 times VEI_t, whereas most of the stable valley-floor reaches had VEI from about 0.7 to 1.0 times VEI_t.

The valley-erosion threshold and reach VEI are empirically derived relations that may be applicable for many reclaimed valley floors in northwestern Colorado. These geomorphic relations may be useful as planning tools in future reclamation projects or in mitigating existing valley-floor instability.

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SUPPLEMENTAL DATA

Table 5.--*Geomorphic and rill-erosion data from selected reclaimed hillslopes*

[Rill frequencies are number of rills per 100 feet of hillslope width; rill densities are total-rill lengths per 100 square feet of hillslope area; ft, feet; ft/ft, feet per foot; ft/100 ft², foot per 100 square feet, --, no data]

Observation	Cumulative hillslope length, L_s (ft)	Incremental hillslope gradient, G_s (ft)	Rill frequency (ft/100 ft²)			Rill density (ft/100 ft²)			Vegetation cover (percent)	Remarks
			Healing	Active	Total	Healing (HD_r)	Active (AD_r)	Total (TD_r)		
				Site 1, TRDP-A, Trapper Mine						
1	50	0.12	0.00	0.50	0.50	0.00	0.40	0.40	--	
2	100	0.14	0.00	0.50	0.50	0.00	0.52	0.52	--	
3	150	0.14	1.00	0.50	1.50	0.30	0.21	0.51	--	
4	200	0.14	1.00	0.50	1.50	0.88	0.51	1.39	85	
5	250	0.16	1.00	0.50	1.50	0.30	0.51	0.81	65	1
6	300	0.18	0.50	0.50	1.00	0.31	0.53	0.84	100	
7	350	0.17	0.00	0.56	0.56	0.14	0.49	0.63	--	2
8	500	0.14	--	--	--	--	--	--	65	
9	550	0.14	--	--	--	--	--	--	85	
10	600	0.20	--	--	--	--	--	--	95	1
11	650	0.25	--	--	--	--	--	--	--	
12	700	0.27	--	--	--	--	--	--	--	
13	750	0.30	--	--	--	--	--	--	--	
14	800	--	--	--	--	--	--	--	100	
15	850	0.32	--	--	--	--	--	--	100	1
16	900	0.32	--	--	--	--	--	--	95	
17	950	0.23	--	--	--	--	--	--	--	
				Site 2, TRDP-B, Trapper Mine						
1	50	0.10	0.50	0.00	0.50	0.06	0.00	0.06	--	
2	100	0.13	0.00	0.50	0.50	0.00	0.18	0.18	--	
3	150	0.13	2.00	0.00	2.00	0.32	0.51	0.83	--	
4	200	0.12	2.00	0.00	2.00	0.57	0.00	0.57	--	
5	250	0.13	1.50	0.00	1.50	1.28	0.00	1.28	100	
6	300	0.16	1.00	0.00	1.00	0.68	0.00	0.68	90	1
7	350	0.20	1.50	0.00	1.50	0.30	0.00	0.30	90	2
8	500	0.19	--	--	--	--	--	--	--	
9	550	0.17	--	--	--	--	--	--	--	
10	600	0.16	--	--	--	--	--	--	--	
11	650	0.17	--	--	--	--	--	--	--	
12	700	0.20	--	--	--	--	--	--	--	
13	750	0.13	--	--	--	--	--	--	--	
14	850	0.19	--	--	--	--	--	--	80	1
15	900	0.18	--	--	--	--	--	--	90	
16	1,300	--	--	--	--	--	--	--	--	1
				Site 3, HGPO-A, Hayden Gulch Mine						
1	50	0.03	0.00	0.00	0.00	0.00	0.00	0.00	--	
2	100	0.06	1.00	0.00	1.00	0.03	0.00	0.03	--	
3	150	0.09	3.00	0.50	3.50	0.66	0.00	0.66	90	
4	200	0.14	1.50	0.00	1.50	2.44	0.52	2.96	90	1
5	250	0.17	2.00	0.00	2.00	1.31	0.00	1.31	75	
6	300	0.19	1.00	0.00	1.00	1.36	0.00	1.36	--	
7	350	0.10	2.50	0.00	2.50	0.50	0.00	0.50	100	
8	400	0.16	1.00	0.00	1.00	1.21	0.00	1.21	100	1
9	450	0.21	0.50	0.00	0.50	1.03	0.00	1.03	95	
10	500	0.24	--	--	--	--	--	--	--	3
11	550	0.26	--	--	--	--	--	--	90	3
12	600	0.28	--	--	--	--	--	--	85	1, 3
13	650	0.28	--	--	--	--	--	--	95	3
14	700	0.25	1.00	1.00	2.00	--	--	--	--	
15	750	0.33	3.00	0.50	3.50	--	--	--	--	

Table 5.--*Geomorphic and rill-erosion data from selected hillslopes*--Continued

Observation	Cumulative hillslope length, L_s (ft)	Incremental hillslope gradient, G_s (ft)	Rill frequency (ft/100 ft^2) Healing	Rill frequency (ft/100 ft^2) Active	Rill frequency (ft/100 ft^2) Total	Rill density (ft/100 ft^2) Healing (HD_r)	Rill density (ft/100 ft^2) Active (AD_r)	Rill density (ft/100 ft^2) Total (TD_r)	Vegetation cover (percent)	Remarks
				Site 4, GGP2-A, Grassy Gap Mine						
1	50	0.08	0.00	0.00	0.00	0.00	0.00	0.00	--	
2	100	0.13	0.00	0.00	0.00	0.00	0.00	0.00	--	
3	150	0.14	0.00	0.00	0.00	0.00	0.00	0.00	95	
4	200	0.15	0.00	0.00	0.00	0.00	0.00	0.00	95	1
5	250	0.14	0.00	0.00	0.00	0.00	0.00	0.00	90	
6	300	0.15	0.56	0.00	0.56	0.13	0.00	0.13	--	
7	350	0.14	0.56	0.00	0.56	0.15	0.00	0.15	80	
8	400	0.12	1.67	0.56	2.23	0.18	0.28	0.46	95	1
9	450	0.13	0.56	1.11	1.67	0.18	0.87	1.05	100	
10	500	0.11	0.00	1.11	1.11	0.18	0.82	1.00	--	
11	550	0.10	3.33	0.56	3.89	0.26	1.07	1.33	40	
12	600	0.13	1.11	0.56	1.67	0.43	0.61	1.04	80	
13	650	0.11	1.11	0.56	1.67	0.08	0.29	0.37	100	1
14	700	0.09	0.00	0.00	0.00	0.12	0.10	0.22	--	
15	750	0.18	0.56	0.00	0.56	0.04	0.00	0.04	--	
16	800	0.17	0.00	0.00	0.00	0.05	0.00	0.05	--	
				Site 5, GGP5-A, Grassy Gap Mine						
1	20	0.01	0.00	0.00	0.00	0.00	0.00	0.00	--	
2	40	0.17	0.00	0.00	0.00	0.00	0.00	0.00	--	
3	60	0.40	0.00	1.85	1.85	0.00	1.25	1.25	85	1
4	80	0.43	1.85	1.85	3.70	0.00	2.05	2.05	--	
5	100	0.44	0.00	0.00	0.00	0.26	1.38	1.64	95	
6	120	0.47	0.00	0.00	0.00	0.00	0.00	0.00	--	
7	140	0.40	0.00	0.00	0.00	0.00	0.00	0.00	90	
8	160	0.46	1.85	1.85	3.70	0.00	0.85	0.85	--	
9	180	0.47	3.70	5.56	9.26	0.00	4.39	4.39	85	
10	200	0.48	3.70	3.70	7.40	0.00	8.34	8.34	--	
11	220	0.46	11.1	1.85	13.0	0.32	6.72	7.04	--	
12	240	0.21	1.85	1.85	3.70	0.00	4.20	4.20	--	
				Site 6, GGP5-C, Grassy Gap Mine						
1	20	0.08	0.00	0.00	0.00	0.00	0.00	0.00	--	1
2	40	0.30	0.00	0.00	0.00	0.00	0.00	0.00	--	
3	60	0.43	0.00	0.00	0.00	0.00	0.00	0.00	85	
4	80	0.41	0.00	0.00	0.00	0.00	0.56	0.56	--	
5	100	0.46	1.85	0.00	1.85	0.12	0.00	0.12	90	
6	120	0.42	3.70	1.85	5.55	0.32	0.47	0.79	--	
7	140	0.49	1.85	3.70	5.55	0.29	2.94	3.23	70	
8	160	0.51	0.00	9.26	9.26	0.55	4.15	4.70	--	
9	180	0.46	0.00	20.4	20.4	0.00	11.9	11.9	80	
10	200	0.44	1.85	0.00	1.85	0.00	9.03	9.03	--	
11	220	0.30	0.00	0.00	0.00	0.26	0.00	0.26	--	
				Site 7, GGP5-E, Grassy Gap Mine						
1	20	0.12	0.00	0.00	0.00	0.00	0.00	0.00	--	1
2	40	0.38	0.00	0.00	0.00	0.00	0.00	0.00	--	
3	60	0.41	0.00	0.00	0.00	0.00	0.00	0.00	70	
4	80	0.52	0.00	0.00	0.00	0.00	0.00	0.00	--	
5	100	0.50	1.85	3.70	5.55	0.08	0.87	0.95	90	
6	120	0.44	3.70	3.70	7.40	0.65	3.11	3.76	--	
7	140	0.48	5.56	9.26	14.8	1.20	6.59	7.79	55	
8	160	0.53	7.41	13.0	20.4	2.70	9.58	12.28	--	
9	180	0.40	11.1	3.70	14.8	6.45	9.07	15.52	78	
10	197	0.19	0.00	0.00	0.00	2.57	2.14	4.71	--	

Table 5.--*Geomorphic and rill-erosion data from selected hillslopes*--Continued

Observation	Cumulative hillslope length, L_s (ft)	Incremental hillslope gradient, G_s (ft)	Rill frequency ($ft/100\ ft^2$)			Rill density ($ft/100\ ft^2$)			Vegetation cover (percent)	Remarks
			Healing	Active	Total	Healing (HD_r)	Active (AD_r)	Total (TD_r)		
					Site 8, EDCR-A, Edna Mine					
1	50	0.07	0.00	0.50	0.50	0.00	0.02	0.02	--	
2	100	0.13	1.00	0.50	1.50	0.07	0.55	0.62	--	
3	150	0.09	1.00	0.50	1.50	0.17	0.22	0.39	--	
4	200	0.06	0.00	0.50	0.50	0.13	0.20	0.33	--	
5	250	0.05	0.00	0.00	0.00	0.00	0.17	0.17	--	
6	300	0.18	0.00	0.00	0.00	0.00	0.00	0.00	95	
7	350	0.22	0.00	0.00	0.00	0.00	0.00	0.00	100	1
8	400	0.27	0.50	0.00	0.50	0.10	0.00	0.10	100	
9	450	0.29	0.00	0.00	0.00	0.08	0.00	0.08	--	
10	500	0.27	0.50	0.00	0.50	0.06	0.00	0.06	95	
11	550	0.28	0.50	0.00	0.50	0.13	0.00	0.13	95	1
12	600	0.31	1.00	0.00	1.00	0.30	0.00	0.30	70	
13	650	0.30	1.50	0.00	1.50	0.89	0.00	0.89	--	
14	700	0.29	4.00	0.00	4.00	2.18	0.00	2.18	70	
15	750	0.31	3.50	0.00	3.50	2.96	0.00	2.96	85	1
16	800	0.26	1.50	0.00	1.50	1.82	0.00	1.82	100	
17	850	0.16	0.50	0.00	0.50	0.51	0.00	0.51	--	
					Site 9, EDCR-B, Edna Mine					
1	50	0.13	0.00	0.00	0.00	0.00	0.00	0.00	--	
2	100	0.20	0.00	0.00	0.00	0.00	0.00	0.00	100	
3	150	0.20	0.00	0.00	0.00	0.00	0.00	0.00	80	1
4	200	0.17	0.00	0.00	0.00	0.00	0.00	0.00	100	
5	250	0.22	2.86	0.00	2.86	1.16	0.00	1.16	--	
6	300	0.31	3.57	0 00	3.57	1.94	0.00	1.94	--	
7	350	0.33	1.43	0.00	1.43	2.08	0.00	2.08	100	
8	400	0.27	0.71	0.00	0.71	0.57	0.00	0.57	95	1
9	450	0.24	0.00	0.00	0.00	0.29	0.00	0.29	85	
10	500	0.25	0.71	0.00	0.71	0.00	0.00	0.00	--	
11	550	0.21	0.71	0.00	0.71	0.51	0.00	0.51	--	
12	600	0.24	0.71	0.00	0.71	0.37	0.00	0.37	95	
13	650	0.23	0.00	0.00	0.00	0.17	0.00	0.17	95	1
14	700	0.22	0.71	0.71	1.42	0.24	0.28	0.52	75	
15	750	0.24	1.43	0.00	1.43	0.69	0.15	0.84	--	
16	800	0.10	0.00	0.00	0.00	0.20	0.00	0.20	--	
					Site 10, EDCR-C, Edna Mine					
1	50	0.05	--	--	--	--	--	--	--	4
2	100	0.13	--	--	--	--	--	--	--	
3	150	0.16	--	--	--	--	--	--	--	
4	200	0.18	--	--	--	--	--	--	--	
5	250	0.12	--	--	--	--	--	--	--	
6	300	0.13	--	--	--	--	--	--	--	
7	350	0.17	--	--	--	--	--	--	--	
8	400	0.25	--	--	--	--	--	--	--	
9	450	0.25	--	--	--	--	--	--	--	
10	500	0.29	--	--	--	--	--	--	--	
11	550	0.30	--	--	--	--	--	--	--	
12	600	0.27	--	--	--	--	--	--	--	
13	650	0.26	--	--	--	--	--	--	--	
14	700	0.26	--	--	--	--	--	--	--	
15	750	0.28	--	--	--	--	--	--	--	
16	800	0.28	--	--	--	--	--	--	--	
17	850	0.27	--	--	--	--	--	--	--	
18	900	0.26	--	--	--	--	--	--	--	
19	939	0.20	--	--	--	--	--	--	--	

[1]Infiltration test and topsoil sample.
[2]Diversion ditch intercepts runoff from upslope and affects rill erosion downslope.
[3]Part of hillslope recently regraded obscuring rill erosion.
[4]Geomorphic data only for all observations at site 10, EDCR-C, Edna Mine.

Table 6.--*Infiltration and topsoil data from selected hillslopes*

[mm/min, millimeters per minute; g/cm^3, grams per cubic centimeter; mm, millimeters; ---, no observation. Particle-size distributions by percent weight. Data from sites with multiple samples are presented in downslope order]

Site	Infil-tration (mm/min)	Bulk density (g/cm^3)	Poros-ity	Percentage finer than											Percent sand
				0.002 mm	0.005 mm	0.009 mm	0.019 mm	0.037 mm	0.074 mm	0.149 mm	0.297 mm	0.590 mm	1.19 mm	2.38 mm	
1	0.0270	1.311	0.362	28.8	34.8	39.2	49.0	63.8	73.2	94.6	98.0	98.8	99.6	100.0	26.8
1	0.3590	1.344	0.401	27.8	33.8	38.4	48.2	62.2	71.1	92.4	97.9	98.7	99.4	100.0	28.9
1	0.1970	1.319	0.407	27.6	33.8	38.4	51.2	65.0	75.3	94.4	98.6	99.1	99.7	100.0	24.7
2	0.2250	1.210	0.490	30.6	38.8	44.4	54.2	70.0	77.0	96.5	98.9	99.4	99.9	100.0	23.0
2	0.1280	1.478	0.421	36.6	43.8	47.4	57.2	74.2	87.4	98.1	99.6	99.8	99.9	99.9	12.6
2	0.1220	1.328	0.392	31.6	40.6	45.0	56.8	77.8	83.7	96.1	98.7	99.2	99.8	100.0	16.3
3	1.0430	1.250	0.493	23.0	33.2	37.8	49.6	64.4	76.4	92.1	98.2	99.1	99.7	100.0	23.6
3	0.4920	1.291	0.426	26.0	36.2	42.8	61.6	67.4	78.6	90.7	98.7	99.7	99.9	100.0	21.4
3	0.7160	1.227	0.439	24.8	35.0	40.6	50.4	66.2	73.8	88.8	98.6	99.6	99.9	100.0	26.2
4	0.0054	1.553	0.403	29.6	42.8	49.6	63.2	76.8	82.7	94.1	96.8	99.4	99.7	100.0	17.3
4	0.3680	1.218	0.484	19.6	27.0	32.8	47.4	60.4	62.6	89.5	97.9	98.9	99.7	100.0	37.4
4	0.0600	1.331	0.432	21.6	31.0	38.8	52.6	72.4	80.5	93.2	96.3	98.1	99.5	100.0	19.5
5	0.0164	1.410	0.430	29.8	39.0	43.8	56.6	73.6	86.7	97.1	98.8	99.4	99.9	100.0	13.3
6	0.0045	1.289	0.414	26.8	36.8	44.6	57.4	74.4	86.2	95.4	97.6	98.8	99.8	100.0	13.8
7	0.0067	1.256	0.451	25.8	33.8	40.4	51.2	70.2	80.6	93.4	98.3	99.3	99.9	100.0	19.4
8	2.8630	1.530	0.255	25.8	34.8	41.4	53.2	72.2	84.8	94.8	97.1	98.3	99.5	100.0	15.2
8	0.0200	1.516	0.246	20.2	26.4	33.0	43.8	61.8	81.8	92.5	95.6	97.6	99.3	100.0	18.2
8	0.1630	1.654	0.258	22.2	31.4	39.0	51.0	66.0	85.4	93.8	97.5	98.8	99.7	100.0	14.6
9	0.2040	1.462	0.263	26.2	35.2	42.0	55.8	77.8	86.2	94.2	98.3	99.3	99.9	100.0	13.8
9	0.0107	1.485	0.256	29.2	39.4	45.0	56.8	72.8	82.3	91.0	97.8	98.9	99.6	100.0	17.7
9	0.1460	1.602	0.229	23.6	29.6	35.0	43.8	55.6	56.8	74.0	98.1	99.1	100.0	---	43.2
11	1.6550	1.312	0.479	19.2	23.4	26.0	30.8	40.6	48.1	91.0	100.0	---	---	---	51.9
11	4.3950	1.368	0.430	20.4	23.4	26.8	35.8	49.6	59.0	91.4	100.0	---	---	---	41.0
11	12.7520	1.030	0.523	20.4	25.4	29.0	36.8	48.8	56.6	86.7	100.0	---	---	---	43.4
12	1.3520	0.997	0.587	22.4	29.2	36.8	43.6	61.6	78.2	91.5	95.1	100.0	---	---	21.8
12	2.0500	0.906	0.579	29.6	38.0	42.2	56.0	74.0	84.7	100.0	---	---	---	---	15.3
12	7.9510	1.050	0.525	18.6	27.2	30.4	42.0	53.0	60.4	75.5	100.0	---	---	---	39.6
13	0.1950	1.241	0.454	33.6	45.0	52.6	65.4	80.2	89.5	95.2	98.2	99.1	100.0	---	10.5
13	0.4910	1.326	0.396	24.6	36.4	43.8	55.6	78.4	88.9	95.3	100.0	---	---	---	11.1
13	6.4320	1.022	0.444	28.6	40.2	48.4	61.2	79.0	90.9	100.0	---	---	---	---	9.1
14	2.0140	1.315	0.346	20.2	25.4	29.4	38.6	50.6	58.3	81.1	100.0	---	---	---	41.7
14	14.5490	1.048	0.504	33.2	41.0	47.0	60.2	76.2	85.7	92.3	100.0	---	---	---	14.3
14	1.3000	1.277	0.460	37.0	44.8	49.8	64.4	78.2	87.0	94.5	100.0	---	---	---	13.0
14	0.8710	1.233	0.427	33.0	40.6	47.8	62.2	78.2	89.7	100.0	---	---	---	---	10.3

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