CHARACTERISTICS OF FLUVIAL SYSTEMS IN THE PLAINS AND DESERTS OF WYOMING

By H.W. Lowham and Mark E. Smith

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 91-4153

Prepared in cooperation with the

U.S. BUREAU OF LAND MANAGEMENT

Cheyenne, Wyoming

1993

U.S. DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
cubic foot per second	0.02832	cubic meter per second
foot	0.3048	meter
foot per foot	1.00	meter per meter
foot per mile	0.1894	meter per kilometer
inch	2.54	centimeter
mile	1.609	kilometer
mile per square mile	0.6212	kilometer per square kilometer
square foot	0.09290	square meter
square mile	2.590	square kilometer

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929--a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

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ABSTRACT

This report describes results of an investigation of geomorphic processes affecting fluvial systems in the energy-resource areas of Wyoming. The purpose of the investigation was to provide information needed for land-use planning and for design of drainage systems that are disturbed by energy-related developments, particularly from surface mining.

Energy-resource development in Wyoming mainly occurs in the plains and desert areas. Flowing water is the major natural force affecting disturbed and reclaimed areas. Streams originating in the plains and deserts are mainly ephemeral, flowing in response to rainstorms and snowmelt. Erosion of basin surfaces and stream channels is predominant during floodflows, which occur only periodically.

Currently, engineering and geomorphic approaches are used in design of reconstructed landscapes. This investigation applies geomorphic principles. Statistical summaries and equations based on measured geomorphic features are presented for design of drainage basins and stream channels for areas that have been disturbed and are in need of reclamation. A qualitative description of natural drainage characteristics was derived from a sample of 124 drainage basins, for which as many as 27 characteristics were measured for each basin. On the basis of these data, statistical summaries and regression relations were developed that can be applied for design of disturbed land areas.

Review of field and laboratory studies of drainage development and sediment yield indicate that reclamation will be relatively more successful if the disturbed area is reconstructed to simulate the landform of an immature basin, rather than of a fully developed drainage network. Greater revegetation success, and smaller sediment loads transported from the reconstructed basin, will occur if first-order streams are not reconstructed, but rather are left to develop naturally.

Statistical summaries and equations, based on measured geomorphic features for design of stream channels that are in need of reconstruction, were derived from an analysis of channel measurements for 68 sites on natural streams in the plains and desert areas. Bankfull flow, which occurs on the average once every 2 years, is considered to be dominant in channel formation and is used as the basis for design of stream channels. After determining bankfull discharge from gaged information or appropriate estimating equations, the cross-section and pattern properties of the stream channel can be determined.

Reclamation of large land areas in the arid and semiarid West has only been done for a few years; there is much to learn concerning methods that are most successful in designing and reconstructing drainage basins. There is a need to establish a data-measurement base for a network of reclaimed basins, especially in view of the great importance and large expense of reclamation. Additional studies of channel pattern and hydraulic-geometry relations for stream channels also are needed.

INTRODUCTION

Development of energy resources commonly involves land disturbances such as roadways, pipelines, oil- and gas-site locations, and surface mines. Surface mining is the most intensive disturbance of large areas of land surface. For example, in northeastern Wyoming, 135 square miles of land surface is projected to be disturbed by existing and proposed surface coal mines, and as much as 253 square miles could be disturbed by all anticipated mining in the area (Martin and others, 1988, p. 118). These developments, which include exploration, extraction, and subsequent reclamation, can alter drainage basins and stream channels. A drainage basin contains a network of interconnected streams, and disturbances can affect the drainage networks and basin surface some distance upstream and downstream, as well as locally.

Many of the land disturbances are occurring on "public lands" owned by the United States and administered by the Secretary of the Interior through the U.S. Bureau of Land Management (BLM). Important to the administration of public lands by the U.S. Bureau of Land Management is the Federal Land Policy and Management Act of 1976 (FLPMA) (U.S. Congress, 1976). The FLPMA requires BLM to ensure that users of the public lands conduct their activities in a manner so as not to cause unnecessary or undue degradation and to complete reasonable reclamation of their disturbances.

Among the goals established by the BLM for reclamation of public lands are long-term stability and conservation. The land-use and activity plans help to establish future expectations of the reclamation process. Depending on the projected or intended uses of a reclaimed area, exact replication of predisturbance conditions might or might not be desirable (Thomas C. Lahti, BLM, written commun., 1991).

This report is the product of a technical investigation of fluvial systems in energy-resource areas of Wyoming. The investigation was done by the U.S. Geological Survey (USGS) in cooperation with the BLM. The purpose of the investigation was to provide information needed for land-use planning and for design of drainage basins and stream channels that are disturbed by energy-related developments, particularly from surface mining in the energy and mineral areas of Wyoming. Energy-resource development in Wyoming mainly occurs in the plains and desert areas, where sedimentary deposits commonly are associated with the formation or capture of deposits such as coal, uranium, oil shale, and oil and gas. This report presents: (1) example case histories of development activities that have caused substantial changes in stream channels and drainage systems; (2) an overview of approaches that are available for design of fluvial systems; (3) a summary of geomorphic characteristics for drainage basins and stream channels in the principal energy and mineral areas; and (4) concepts, methods, and examples for geomorphic design of disturbed drainage basins and stream channels for areas that are in need of reclamation.

Acknowledgments

The assistance of Stephen Parsons (formerly with the BLM and now with U.S. Office of Surface Mining), Bruce Van Haveren (BLM), and Mike Brogan (BLM) in providing suggestions for approach to the investigation is gratefully acknowledged.

Fluvial Processes

Flowing water is the major natural force affecting disturbed and reclaimed land in the energy-resource areas of Wyoming. Streamflows are highly variable throughout the State, partly because of the effect that mountain ranges have on the quantity of precipitation and resulting runoff. A recent comprehensive study of streamflows in Wyoming by Lowham (1988, p. 18) describes the distinct runoff characteristics that exist for different regions of the State. Three regions--mountainous, plains, and high desert--were defined on the basis of climate, topography, and geology. Although several major rivers flow across the plains and high desert regions, the main source of perennial flow to these rivers is from snowmelt in the mountainous regions (fig. 1).

Streams originating in the semiarid and arid plains and high desert regions generally are ephemeral, flowing in direct response to rainstorms and snowmelt. Although these streams do not have sustained flows throughout the year, they do have periodic flows and occasional floodflows. Erosion of basin surfaces and stream channels is predominant during floodflows. Floods can result either from rainstorms or snowmelt; however, the largest floods result from convective rainstorms, which occur in Wyoming most frequently in the northern and eastern plains (fig. 1). Relatively smaller floods occur in the south-central and southwestern plains and high desert regions, where precipitation occurs more frequently in the form of less-intense rainstorms and snow, and less frequently from convective storms.

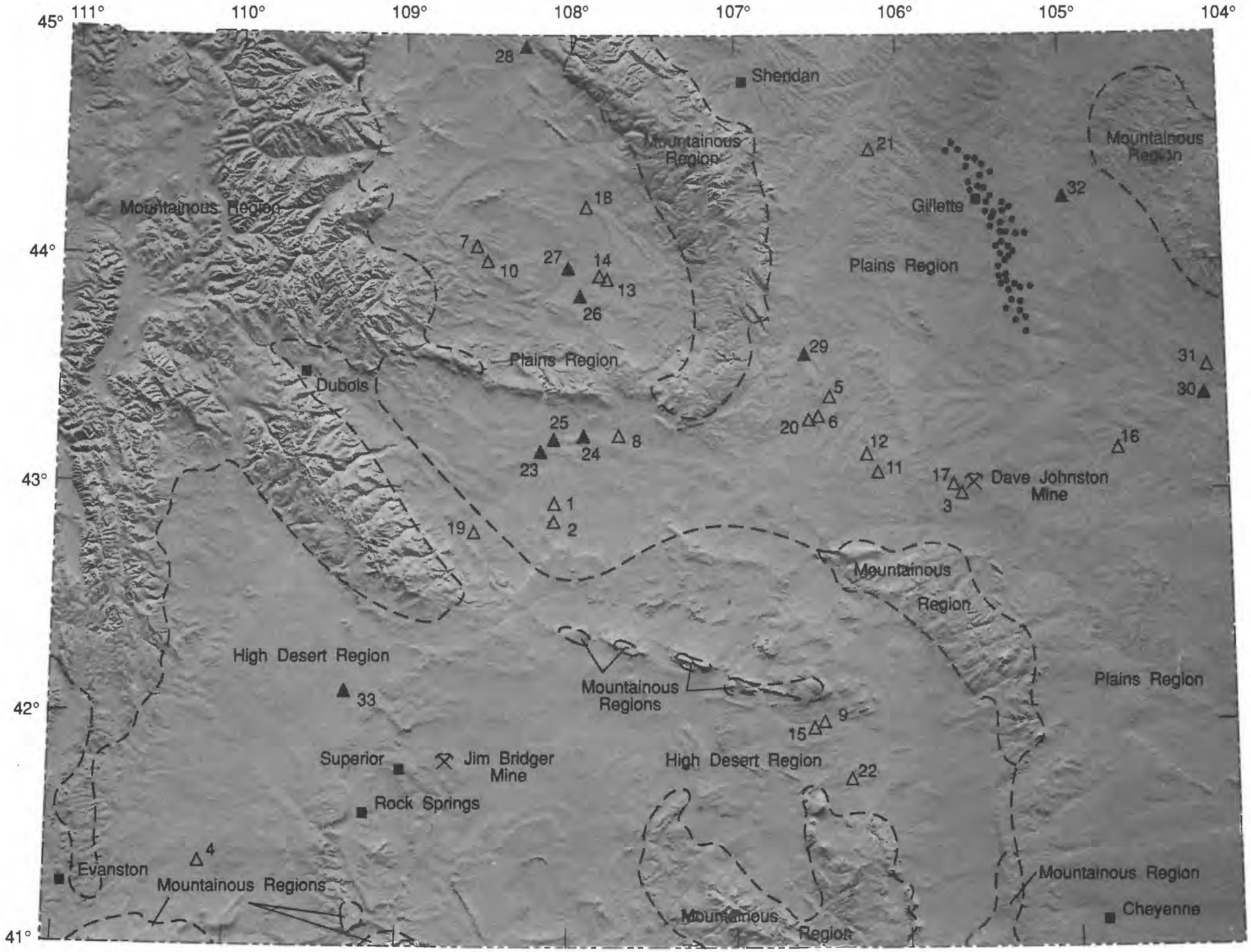
Floodflows large enough to affect the landscape in the plains and desert regions are infrequent, especially in small basins. In drainage basins of a few square miles or less, it is common for several years to pass between periods of substantial runoff. Changes in the fluvial system of a disturbed drainage basin might not be apparent until several large streamflows have occurred, which could take several decades before they occur. Although readily visible responses such as rilling and gullying could soon occur where unstable areas are not reclaimed, it also is possible that only a gradual response would take place for several years until a substantial runoff occurs.

CASE HISTORIES OF THE EFFECTS OF HUMAN ACTIVITIES ON FLUVIAL SYSTEMS

Human activities can have substantial effects on fluvial systems and water quality. In many cases, when the activity takes place it is not realized that detrimental effects can result, especially adjustments in stream channels and drainage networks distant from local activities. Case histories of activities that have resulted in detrimental effects to fluvial systems follow as illustrative examples.

Surface Mining

Surface mining alters the natural landscape. Until the affected area is reclaimed, erosion and sediment yields can be much greater than natural rates. Since enactment of the Surface Mining Control and Reclamation Act of 1977 (U.S. Congress, 1977), land disturbed by surface mining must be reclaimed. Prior to such reclamation laws, surface mines commonly were left without suitable reclamation. For example, an area in the Hidden Water Creek basin about 12 miles northwest of Sheridan was mined for coal during 1949 to 1955, and was left without reclamation (fig. 2).



Base for shaded relief from U.S. Geological Survey composite of 1:250,000 quadrangles, computer-generated experimental product made from digital terrain tapes, 1979.

Base for cultural names, drainage and roads from U.S. Geological Survey Wyoming State base maps, 1:500,000.

0 25 50 75 100 MILES

0 25 50 75 100 KILOMETERS

EXPLANATION

- — — — BOUNDARY OF HYDROLOGIC REGION—(Lowham, 1988, pl. 1).
- △22 MEASURED DRAINAGE BASIN, STREAMFLOW-GAGING STATION, AND SITE NUMBER— (From Craig and Rankl, 1978, fig. 1).
- ▲33 STREAMFLOW-GAGING STATION AND SITE NUMBER—Used to develop hydraulic-geometry relations.
- • MEASURED DRAINAGE BASIN—(From Martin and others, 1988, p.124-130)

Figure 1.--Hydrologic regions and location of drainage basins used to determine natural characteristics.

Figure 2.--Mined area of Hidden Water Creek near Sheridan before reclamation (1980). Photograph courtesy of HKM Associates, published with permission of Bruce Yates, HKM Associates, and Gary Beach, Director, Abandoned Mine Lands Program, Wyoming Department of Environmental Quality.

The analysis of sediment-deposition data collected for two ponds in the area indicated 11 times greater sediment yield from the mined drainage area than from an adjacent unmined drainage area (Ringen and others, 1979, p. 11). The mined area was reclaimed in 1987 as part of the Abandoned Mine Reclamation program (G.G. Beach, Wyoming Department of Environmental Quality, oral commun., 1987).

Underground Mining

Alteration of fluvial systems also can occur from activities other than intensive land disturbances such as surface mining. For example, Bitter Creek, an intermittent stream that drains the plains and desert east of Rock Springs, and many of its tributaries have deep gullies that have been caused by a cumulation of land-use activities (Lowham, 1982, p. 41-48). At least part of the gullying, especially of Horsethief Canyon and Killpecker Creek, is attributed to dewatering of underground coal mines. The produced waters were released into these formerly ephemeral tributaries of Bitter Creek, aggravating erosion and downcutting of the streambeds and associated degradation of the drainage basin (fig. 3).

Figure 3.--Gully of Horsethief Canyon near Superior (February 1990). Depth of gully at this site is about 15 feet.

Tie Drives

The building of the transcontinental railroad in 1867 spurred the timber industry to supply timber for railroad ties and for ties and supports used in the underground mines that supplied coal to the railroad. Streams were used to transport timber from the forests to the railheads. The transport, which required high streamflows, was accomplished either during floodflows (fig. 4) or through the use of splash dams.

The splash dam was built of timbers across the stream, and the harvested timbers were stored in the resulting pond or just downstream from the dam. When the pond reached capacity, the spill gate in the splash dam was removed, and the resulting surge of water sluiced the stored logs down the stream toward the sawmill. Alterations of the stream channel, including blocking of sloughs and low meadows, blasting or removing boulders, and removing encroaching riparian vegetation, commonly were used to ensure a swift trip without jams or loss of timbers. These activities altered stream channels to the extent that the effects are still visible (Schmal and Wesche, 1989, p. 189).

Figure 4.--Boom and tie drive in the Wind River drainage basin near Dubois, about 1930. Photograph courtesy of American Heritage Center, Cole Library, University of Wyoming, published with permission.

Urbanization and Channelization

The city of Evanston had substantial growth during the early 1980s as a result of oil-and-gas activities in southwestern Wyoming. During the rapid growth, many new commercial developments were constructed along the Bear River that substantially altered the channel of the river through Evanston.

The channel alteration was compounded by large floodflows in 1983 and 1984. During that time, landowners along the stream attempted to protect their properties from flood damage by building dikes and placing material along the streambanks. These latest channel alterations added to channelization that began in the 1920s, resulting in a 3-mile reach of natural channel being shortened by more than 1 mile (fig. 5).

As a result of these cumulative changes, the stream channel reached a condition of instability and began downcutting. The streambed and streambanks eroded, and large volumes of material were washed into reaches of the river downstream from the city. These deposits clogged the channel and caused it to widen from its natural width of about 120 feet to as wide as 400 feet, with multiple distributary channels. The streambed of the channelized reaches downcut as much as 3 feet in some reaches, and the channel upstream became susceptible to headcutting. Thus, the reach of river that eventually was affected extended both upstream and especially downstream much beyond the original channelized reach.

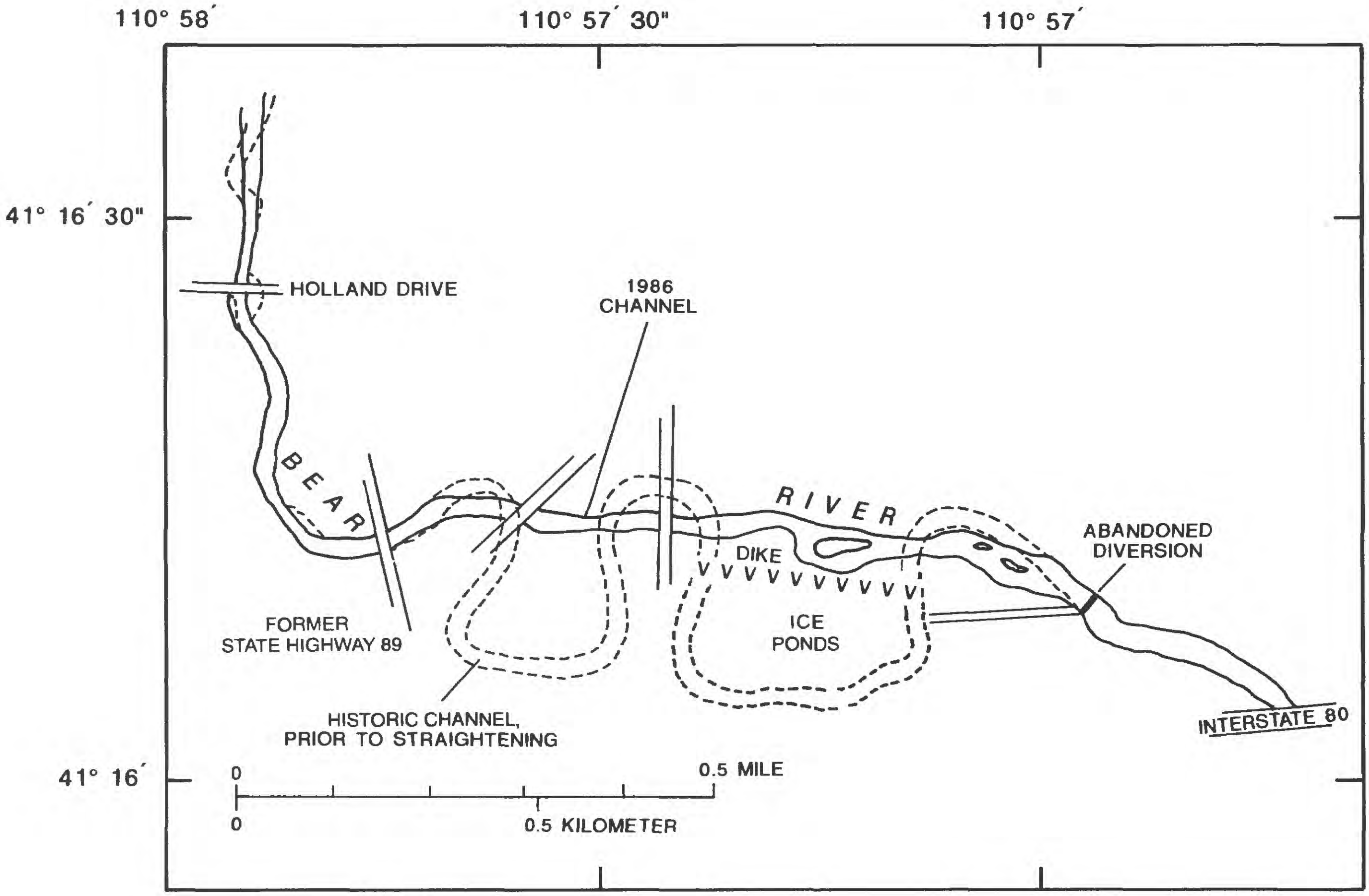


Figure 5.--Plan view of a shortened channel reach of the Bear River at Evanston.

APPROACHES FOR THE DESIGN OF FLUVIAL SYSTEMS

There are two basic approaches, geomorphic and engineering, for the design of fluvial systems following destruction by land disturbances. As discussed by Toy and Hadley (1987, p. 236), problems are encountered with each approach. The geomorphic approach is based on design and reconstruction of drainage basins and stream channels to simulate the natural characteristics of an undisturbed area; however, there have been few onsite studies that document the successful use of geomorphic principles for large mined areas in the arid and semiarid western United States. The engineering approach is based on design of the drainage network and stream channels to accommodate the water and sediment discharges expected following disturbance and reconstruction; however, it usually is necessary to estimate water and sediment discharges, which consequently are approximate.

Geomorphic Approach

The application of a geomorphic approach to the design of postmining fluvial systems is based on the assumption that runoff, lithology, soil, and vegetative cover will be similar before and after mining. Following mining and reclamation, infiltration and runoff are expected to return to normal after about 6 years (Martin and others, 1988, p. 106). Although reclamation is directed toward the re-establishment of soil and vegetative cover, lithology cannot be re-established. Many of the first- and second-order stream channels for natural drainage basins have steep slopes that are supported by outcrops of erosion-resistant rocks. If such outcrops are not present in the postmining drainage basins, then slopes indicated by the geomorphic relations might be steeper than the reclaimed areas of spoil material actually can support. As surface mining progresses, documentation of successes and failures in the re-establishment of drainage basins is needed to assist in the refinement of design methods.

Engineering Approach

The engineering approach to design of fluvial systems generally relies on estimates of streamflow and sediment loads; engineering design of stable stream channels also requires estimates of roughness factors. Because estimates are used, the designs are approximate and it is possible that some stream channels might be misdesigned. Local sedimentation and erosion might occur as misdesigned stream channels attempt to adjust to the surrounding conditions.

Methodologies for using engineering design are not discussed in this report, as they are adequately described in available publications. A text by Barfield and others (1981) describes engineering design, including elements of hydrologic and hydraulic principles, soil erosion and sediment yield, and design of erosion and sediment controls. A report by Jones and others (1988) provides guidance on construction methods that might be employed in abandoned mine land reclamation.

Design Goals

The ideal procedure for reclaiming mined areas is to construct a drainage network that would optimize overall stability and immediately minimize erosion and sediment transport. However, the realities of the state-of-the-art regarding drainage-basin and stream-channel design, as well as construction techniques, make this impossible. For example, even if the perfect drainage-basin and stream-channel design were implemented, unpredictable differential settling of the spoil material is likely to occur that would affect the hydrologic characteristics of the drainage basin.

The design of stable drainage basins for postmining areas is critical to the type and degree of use the land might support after reclamation. According to Bishop (1980, p. 249), the more closely that postmining topography can be restored to match up with surrounding undisturbed areas and approximate original contours, the greater the likelihood of stable drainage networks and successful reclamation. Natural drainage networks and stream channels have evolved during long periods. Thus, they are considered to be in equilibrium with the climatic and physical conditions of their basins. In referring to natural landscapes and stream channels, the term "stability" means "dynamic stability." Drainage basins and stream channels evolve as they are subjected to forces such as tectonism, climate, runoff, and use by humans and animals.

Although geomorphic analysis of drainage basins and stream channels is a fairly new approach for design of reclaimed surface mines, investigators have used the methodology successfully to assess changes and assist with design of other stream-related developments. For example, Patton and Schumm (1975) quantified a relation between valley-floor slope and drainage area for small drainage basins in the area near Piceance Creek in Colorado, whereby a threshold slope was identified above which trenching or valley instability would occur. Valley-floor erosion for reclaimed drainage basins of surface-coal mines in northwestern Colorado has been related by Elliott (1989) to three geomorphic variables: drainage area, valley gradient, and valley-floor width. Dunne and Leopold (1978, p. 22-28) described the use of geomorphology and hydrology for land-use planning in the valley associated with the mobile channel of the Yakima River near Yakima, Washington. Lowham and others (1982, p. 40-45) examined severe gullying in the Salt Wells Creek basin near Rock Springs, Wyoming, and determined the causes and approximate period of occurrence.

GEOMORPHIC DESIGN OF FLUVIAL SYSTEMS

Geomorphic analysis involves measuring fluvial characteristics for undisturbed areas and applying summaries and relations of these data in the design of areas that are disturbed and in need of reclamation. Data for the undisturbed areas are used on the assumption they represent natural and stable fluvial systems. A measure of the stability of fluvial systems in the semiarid and arid regions of the western United States was implemented in 1962 through the Vigil Network (Leopold, 1962), whereby representative ephemeral draws, gullies, and stream channels were selected and instrumented to measure channel changes with time. Instrumentation of small tributaries was done with the intent of measuring channel changes resulting from changes in precipitation and runoff as well as those resulting from human activities.

From measurements made at eight Vigil Network sites in the semiarid and arid western United States, including several sites in Wyoming, Emmett (1974, p. 53-54) concluded that the valley trenching that began about 1880 has now decreased, and that stream channels are stable or aggrading. Observations of stream channels in Wyoming since the 1960s support the conclusion that, in general, the fluvial system currently (1991) is stable. Although some localized gullying and headcutting are occurring, caused by adjustments to local land uses, changes to the fluvial system overall appear to be related to natural erosional development and rejuvenation. For example, a discontinuous channel west of Gillette is shown in figure 6. The drainage basin and stream

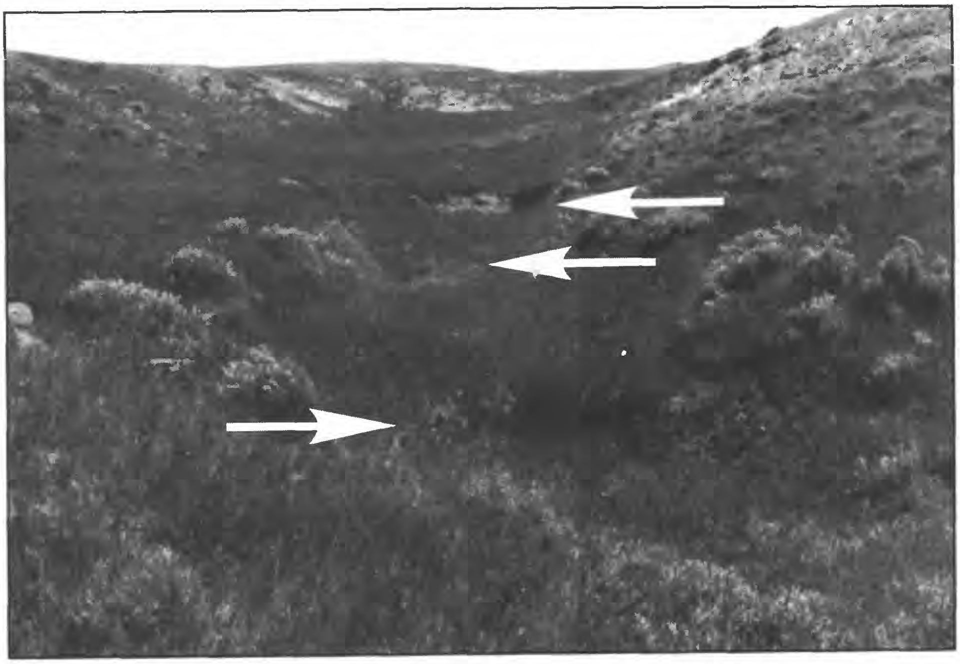


Figure 6.--Example of discontinuous channel with slowly advancing headcuts as part of a naturally changing landscape (1988).

channel are typical of others in the area, with local changes such as small, slowly advancing headcuts developing as part of a naturally changing landscape.

Drainage Basins

The drainage basin is the unit most basic to reclamation of the large areas affected by mining. A drainage basin is composed of two basic features: (1) a network of stream channels, and (2) the interfluve, which consists of valley and hillslope areas between stream channels. Stream channels and hillslopes are interrelated--what happens on the interfluve between streams has a dominant effect on the character of streams and on the hydrology of the basin (Chorley and others, 1984, p. 258). The drainage network of a drainage basin is defined as the number and form of all stream channels in the basin. When surface geology is fairly uniform throughout a drainage basin, the drainage network tends to develop in a dendritic pattern, as is shown in figure 7.

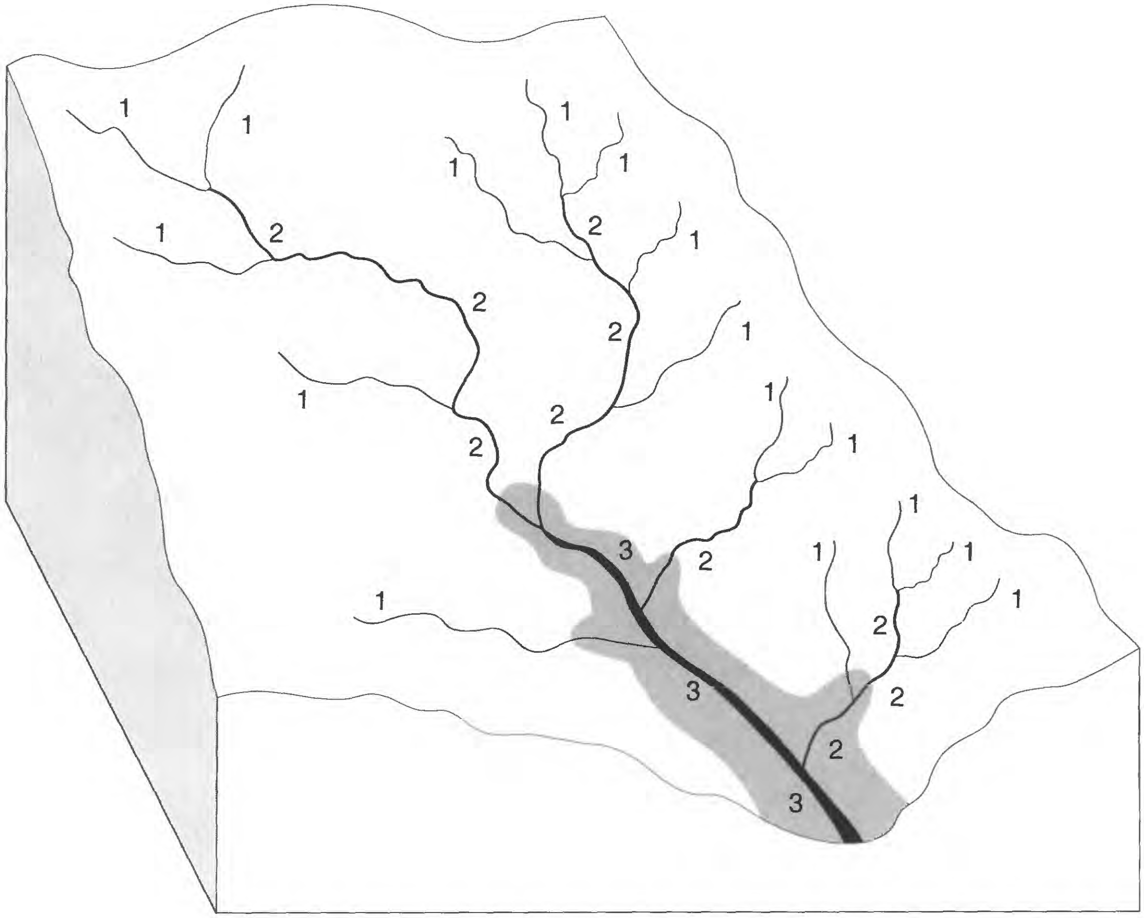


Figure 7.--Drainage network with a dendritic pattern in a third-order drainage basin showing first-, second-, and third-order streams.

A quantitative description of physical characteristics for natural fluvial systems was made for this study using a method commonly referred to as the Horton analysis (Horton, 1945). The fundamental aspect of the Horton analysis is the relation of certain physical characteristics, such as drainage area, number of stream channels, and channel length, to stream order. Stream order is defined as the position of a stream channel within a drainage network (fig. 7). The ordering system described by Strahler (1957, p. 914) was used in this analysis. The smallest stream channels of the network are unbranched tributaries, which are designated as first-order streams. When two first-order streams join, the resulting stream channel is a second-order stream. Third-order streams receive two or more tributaries of the second order, but also can receive first-order streams, and so on. In this system, the main stream has the highest order. The order of the main stream indicates the order of the drainage basin.

Stream order generally is determined by examining the drainage network of a basin on topographic maps. The map scale limits the size of the smallest stream channel that can be recognized. To include the smallest rills evident in the drainage basin in stream ordering, several orders of streams might have to be added to the smallest streams shown on 1:24,000-scale topographic maps (Leopold and Miller, 1956, p. 16). However, the inclusion of small rills in a drainage-net analysis is useful only for special studies. For most purposes, one may restrict consideration to the drainage network appearing on 1:24,000-scale topographic maps (Leopold and others, 1964, p. 141).

Visits to selected measured drainage basins and stream channels were made to compare features observed in the field with those depicted on topographic maps. The comparison indicated that rills, some swales, and some small stream channels are not shown on the maps; however, the number and detail of the blue lines symbolizing streams and the contour lines showing other physical features on recent 1:24,000-scale topographic maps are considered adequate to define the fundamental aspects of natural drainage basins and stream channels. It was observed that maps dated pre-1960 showed relatively less detail for streams than maps dated post-1960. The differences apparently are because of refinements in mapping techniques.

Characteristics of Natural Drainage Basins

The physical characteristics of natural drainage basins in the plains and high desert regions of Wyoming were defined on the basis of an expanded data base for sites investigated in two previous studies: (1) 102 drainage basins in northeastern Wyoming (Martin and others, 1988, p. 124-134), and (2) 22 drainage basins located statewide, at which precipitation and streamflow data were collected during the 1970s as part of a rainfall-runoff analysis (Craig and Rankl, 1978). Locations of the measured basins are shown in figure 1, along with boundaries of the hydrologic regions as defined by Lowham (1988, p. 18). The selected drainage basins are considered natural, but can include human-controlled land uses common to Wyoming, such as grazing of livestock and the presence of roads, powerlines, and small stock ponds.

Fifteen physical characteristics were measured for each of the first-order basins, and 27 physical characteristics were measured for each of the second- or higher order drainage basins. Because of limitations of the map scale, some of the characteristics measured for the second- or higher order drainage basins could not be accurately measured for the smaller first-order drainage basins. A description of each of the characteristics is given in table 1; the measured values are listed in tables 2 and 3.

A statistical summary of the values of the physical characteristics is given in tables 4-7 for each of the drainage basin orders. The tables list the minimum and maximum values measured, the arithmetic mean, the geometric mean, and the standard deviation of the sample. The arithmetic and geometric means for each of the characteristics indicate the expected average magnitudes. The geometric mean, which is computed using logarithms of the values, generally is considered a more representative descriptor of the central tendency of distributions in hydrology than the arithmetic mean, because the distributions usually are asymmetrical.

Table 1.--Description of measured drainage-basin characteristics

[*, the only characteristics that could be measured for first-order basins]

Characteristic	Description
*Drainage area	The area, measured in a horizontal plane, from which direct surface runoff from precipitation normally drains into the stream channel upstream from the specified point, in square miles.
Number of first-order channels	Total number of stream channels in the drainage basin that are classified as first order.
Number of second-order channels	Total number of stream channels in the drainage basin that are classified as second order.
Number of third-order channels	Total number of stream channels in the drainage basin that are classified as third order.
Number of fourth-order channels	Total number of stream channels in the drainage basin that are classified as fourth order.
Length of first-order channels	Summation of lengths of all stream channels classified as first order, in miles.
Length of second-order channels	Summation of lengths of all stream channels classified as second order, in miles.
Length of third-order channels	Summation of lengths of all stream channels classified as third order, in miles.
Length of fourth-order channels	Summation of lengths of all stream channels classified as fourth order, in miles.
*Basin length	Straight-line distance from the point on the drainage divide nearest the head of the dominant channel to the mouth of the drainage basin, in miles.
*Basin perimeter	Total distance along the drainage divide that defines the boundary of the drainage basin, in miles.
Basin width	Representative width of the drainage basin, generally measured between the drainage divides at about the midpoint of the basin, in miles.
*Valley length	Length of the valley for the dominant stream channel symbolized by the blue line for the stream on a 1:24,000-scale topographic map, in miles. The valley length is measured along the general course of the stream, but does not include the stream meanders.
*Channel length	Length of the dominant stream channel measured along the blue line symbolizing the stream on a 1:24,000-scale topographic map, in miles.

Table 1.--Description of measured drainage-basin characteristics--Continued

Characteristic	Description
*Basin relief	Difference in elevation between the point on the drainage divide nearest the head of the dominant stream channel and the mouth of the drainage basin, in feet.
*Used relief	Difference in elevation between two points on the stream channel, in feet. For the first-order basins, the points were selected at each end of the blue line symbolizing the stream on a 1:24,000-scale topographic map. For the second- and higher-order basins, the points were selected at 15 and 85 percent of the dominant stream-channel length.
*Channel slope	Used relief divided by the length of stream channel between the points identified in used relief, in foot per foot. This depicts an average slope of the stream channel, which should not be confused or compared with values that are measured at particular locations along stream channels.
Basin order	Order of the stream channel at the drainage-basin mouth.
*Sinuosity	Channel length divided by valley length. This depicts an average sinuosity for the stream channel, which should not be confused with values that are measured at particular locations along stream channels.
*Relief ratio	Basin relief divided by basin length, in feet per mile.
*Total channel length	Summation of lengths of all stream channels of all orders in the entire drainage basin, in miles. For first-order streams, this is the same as channel length.
*Drainage density	Total channel length divided by the drainage area, in miles per square mile.
*Circularity ratio	Area of the drainage basin divided by the area of a circle having the same perimeter as the drainage basin.
*Stream frequency	Total number of streams of all orders divided by the drainage area, in number of streams per square mile.
Maximum side-slope relief	Difference in elevation between the hilltop and the stream at a location in the valley where sideslope is steepest, in feet.
Sideslope distance	Straight-line distance measured in a horizontal plane between the hilltop and the stream channel at the same point as the maximum sideslope relief was measured, in miles.
*Maximum value sideslope	Maximum value of sideslope relief divided by the sideslope distance, in foot per foot.

Table 2.--Physical characteristics for first-order drainage basins

Map name[1] or station[2] number	Drainage area (square miles)	Basin length (miles)	Basin perimeter (miles)	Valley length (miles)	Channel length (miles)	Basin relief (feet)	Used relief (feet)	Channel slope (foot per foot)	Sinuosity	Relief ratio (feet per mile)	Drainage density (miles per square mile)	Circularity ratio	Stream frequency (streams per square mile)	Maximum value side-slope (foot per foot)
Calf Creek	0.12	0.57	1.48	0.41	0.41	160	100	0.0452	1.00	279	3.52	0.676	8.40	0.100
Calf Creek	.21	.56	1.83	.63	.67	125	40	.0112	1.07	223	3.25	.774	4.81	.097
Calf Creek	.15	.89	2.11	.85	.93	130	110	.0224	1.09	146	6.12	.426	6.58	.071
Calf Creek	.10	.58	1.35	.43	.43	290	70	.0308	1.00	502	4.48	.655	10.4	.095
Fortin Draw	.12	.73	1.67	.47	.49	150	70	.0268	1.04	207	3.95	.558	8.00	.133
Rawhide School	.15	.67	1.85	.66	.65	160	80	.0230	1.00	240	4.48	.539	6.80	.063
Moyer Springs	.31	1.05	2.74	.87	.96	130	70	.0138	1.10	124	3.12	.515	3.25	.086
Rawhide School	.19	.56	1.71	.43	.43	70	50	.0217	1.01	126	2.34	.799	5.38	.045
Rawhide School	.24	.99	2.29	.91	.92	145	105	.0215	1.00	147	3.81	.577	4.13	.046
Rawhide School	.07	.53	1.25	.47	.52	185	150	.0542	1.10	347	7.18	.583	13.7	.074
Gillette West	.17	.68	1.93	.62	.73	300	160	.0414	1.18	443	4.31	.573	5.88	.074
Gillette East	.43	1.20	2.88	.99	1.22	140	110	.0171	1.22	117	2.85	.646	2.34	.045
Gillette West	.39	1.04	2.75	.62	.62	130	30	.0091	1.00	125	1.61	.642	2.58	.020
Gillette East	.25	.67	1.95	.52	.55	100	60	.0204	1.05	150	2.21	.827	3.97	.014
Gillette East	.24	.66	2.14	.42	.49	200	40	.0152	1.17	301	2.11	.640	4.26	.049
Gillette East	.14	.59	1.76	.51	.56	160	130	.0436	1.10	269	4.19	.547	7.41	.060
Gillette East	.07	.68	1.50	.67	.67	170	140	.0392	1.00	252	9.66	.387	14.3	.058
Gillette East	.35	1.39	3.38	1.31	1.38	180	150	.0205	1.06	130	3.94	.385	2.85	.103
Gillette East	.18	.58	2.42	.49	.54	70	60	.0208	1.11	120	3.06	.381	5.59	.046
Coyote Draw	.25	1.00	2.68	.72	.79	115	95	.0225	1.11	115	3.24	.430	4.07	.039
The Gap	.49	1.26	3.35	.63	.67	100	40	.0112	1.06	79	1.37	.551	2.02	.033
Coyote Draw	.32	1.06	2.90	.82	.93	140	60	.0121	1.13	133	2.91	.479	3.11	.076
The Gap	.10	.59	1.67	.53	.56	165	65	.0219	1.06	279	5.93	.428	10.5	.046
Coyote Draw	.24	.92	2.56	.65	.69	140	60	.0165	1.05	152	2.88	.458	4.17	.052
Coyote Draw	.10	.63	1.43	.50	.51	80	50	.0186	1.01	128	4.86	.645	9.52	.033
Coyote Draw	.10	.98	2.18	.58	.58	90	30	.0097	1.00	92	5.55	.277	9.52	.014
The Gap	.04	.44	1.03	.36	.38	130	90	.0444	1.05	292	9.60	.472	25.0	.158
The Gap	.34	.89	2.26	.76	.96	120	60	.0117	1.27	134	2.81	.843	2.90	.083
Coyote Draw	.25	1.02	2.61	.78	.85	140	80	.0178	1.09	137	3.38	.461	3.97	.147
Coyote Draw	.16	.50	2.27	.39	.44	140	50	.0211	1.13	279	2.78	.391	6.21	.078

Table 2.--Physical characteristics for first-order drainage basins--Continued

Map name[1] or station[2] number	Drainage area (square miles)	Basin length (miles)	Basin peri-meter (miles)	Valley length (miles)	Channel length (miles)	Basin relief (feet)	Used relief (feet)	Channel slope (foot per foot)	Sinu-osity	Relief ratio (feet per mile)	Drainage density (miles per square mile)	Circu-larity ratio	Stream frequency (streams per square mile)	Maximum value side-slope (foot per foot)
Saddle Horse Butte	0.12	0.43	1.40	0.34	0.34	120	60	0.0329	1.01	278	2.92	0.748	8.47	0.088
Saddle Horse Butte	.08	.55	1.40	.44	.47	90	70	.0279	1.06	164	5.94	.508	12.5	.081
Saddle Horse Butte	.09	.62	1.49	.49	.49	100	60	.0229	1.00	160	5.29	.530	10.6	.050
Neil Butte	.05	.47	1.15	.30	.30	150	80	.0505	1.00	317	6.52	.431	21.7	.074
Neil Butte	.30	.96	2.40	.73	.73	215	175	.0454	1.00	224	2.42	.655	3.31	.219
Eagle Rock	.08	.54	1.34	.54	.54	260	150	.0523	1.00	479	6.96	.542	12.8	.059
Neil Butte	.13	.63	1.65	.47	.54	290	120	.0414	1.17	461	4.10	.614	7.46	.040
Neil Butte	.07	.58	1.36	.52	.55	90	80	.0274	1.06	155	7.77	.479	14.1	.047
Neil Butte	.07	.38	1.13	.29	.29	65	30	.0191	1.02	172	4.08	.709	13.7	.059
Neil Butte	.16	.72	2.00	.68	.72	70	60	.0158	1.04	97.0	4.50	.502	6.25	.037
Neil Butte	.04	.32	.85	.21	.21	60	40	.0349	1.00	185	4.93	.765	22.7	.077
Reno Reservoir	.25	1.12	2.65	.81	.95	110	80	.0159	1.17	98.0	3.78	.449	3.97	.293
Hilight	.16	.49	1.67	.45	.45	115	35	.0146	1.00	236	2.89	.700	6.37	.075
Hilight	.22	.69	2.15	.61	.61	200	150	.0461	1.00	290	2.75	.605	4.46	.165
Hilight	.12	.96	2.15	.77	.84	210	110	.0246	1.09	218	6.99	.328	8.26	.025
Hilight	.11	.53	1.33	.43	.49	45	25	.0096	1.12	85.2	4.63	.747	9.43	.081
Hilight	.25	1.09	2.56	.70	.78	80	40	.0096	1.11	73.2	3.14	.476	4.00	.015
Open A Ranch	.13	.66	1.92	.66	.66	130	120	.0343	1.00	196	5.18	.432	7.81	.263
The Gap SW	.22	.84	2.42	.78	.81	160	120	.0280	1.03	191	3.78	.460	4.65	.104
Saddle Horse Butte	.13	.81	1.87	.61	.65	170	130	.0376	1.06	210	4.92	.477	7.52	.174
The Gap SW	.46	1.32	3.80	.95	.96	75	53	.0104	1.01	56.6	2.08	.400	2.16	.042
06238760 (1)	.68	1.43	4.34	1.10	1.15	80	60	.0100	1.05	55.9	1.69	.453	1.47	.067
06238780 (2)	1.85	2.14	6.02	1.90	1.96	180	140	.0140	1.03	84.1	1.06	.641	.54	--
06648780 (3)	1.38	2.52	6.45	2.39	2.60	335	240	.0190	1.09	133	1.88	.422	.72	.064

[1] U.S. Geological Survey 1:24,000-scale topographic map. Data for these sites are modified from Martin and others (1988, p. 124-130).
[2] U.S. Geological Survey streamflow-gaging station number and site number (in parentheses) shown in figure 1. Data for these sites are modified and expanded from Craig and Rankl (1978, p. 25).

Table 3.--Physical characteristics for second-,

Map name[1] or station[2] number	Basin order	Drainage area (square miles)	Number of channels, for indicated order number of channel: 1st	2nd	3rd	4th	Total length of channels, in miles, for indicated order number of channel: 1st	2nd	3rd	4th	Basin length (miles)	Basin perimeter (miles)	Basin width (miles)	Valley length (miles)
Calf Creek	3	0.74	5	2	1	0	1.42	1.28	0.62	0.00	1.66	4.28	0.47	1.50
Calf Creek	4	7.73	34	11	2	1	12.0	7.60	3.31	4.14	5.29	13.0	1.97	4.97
Calf Creek	2	.91	3	1	0	0	2.51	.48	.00	.00	1.42	3.88	.84	1.25
Calf Creek	2	.71	5	1	0	0	1.06	1.64	.00	.00	1.67	4.05	.52	1.50
Fortin Draw	2	.51	3	1	0	0	1.55	.95	.00	.00	1.57	3.64	.42	1.38
Rawhide School	4	3.22	16	6	2	1	5.79	2.98	.70	1.35	2.95	7.68	1.55	2.92
Moyer Springs	3	2.12	11	5	1	0	5.95	2.03	1.86	.00	2.37	6.94	.98	1.99
Rawhide School	2	.88	4	1	0	0	1.36	1.69	.00	.00	1.85	5.09	.47	1.85
Rawhide School	3	3.24	10	3	1	0	4.81	3.93	.96	.00	2.78	9.02	1.10	2.42
Rawhide School	3	1.88	6	2	1	0	3.34	2.23	.36	.00	2.21	5.89	1.09	1.89
Gillette West	3	3.41	8	2	1	0	5.20	1.57	2.30	.00	3.16	8.35	1.35	3.03
Gillette East	2	.93	4	1	0	0	2.69	1.32	.00	.00	2.37	5.10	.51	2.29
Gillette West	2	1.38	5	1	0	0	2.34	.36	.00	.00	1.71	5.10	1.02	1.68
Gillette East	4	8.18	13	4	2	1	7.51	5.02	6.87	.80	6.32	14.7	1.91	6.00
Gillette East	3	2.78	6	2	1	0	4.71	2.03	2.40	.00	3.32	8.32	1.06	3.20
Gillette East	3	1.55	5	2	1	0	2.98	1.51	.10	.00	1.26	5.92	.81	1.20
Gillette East	2	.40	2	1	0	0	.98	.55	.00	.00	1.10	2.80	.41	1.05
Gillette East	3	3.33	16	4	1	0	7.32	4.62	2.18	.00	3.89	9.52	1.20	3.76
Gillette East	3	2.13	5	2	1	0	1.89	1.61	.67	.00	2.48	8.01	.70	2.16
Coyote Draw	3	2.15	8	2	1	0	4.31	2.83	.90	.00	2.86	6.97	.87	2.58
The Gap	3	4.16	10	3	1	0	6.55	3.25	2.28	.00	3.80	10.1	1.61	3.77
Coyote Draw	4	4.45	15	4	2	1	8.88	2.94	1.40	1.14	4.43	12.6	1.31	3.64
The Gap	2	1.04	3	1	0	0	1.52	1.96	.00	.00	2.12	4.96	.74	2.12
Coyote Draw	3	1.24	8	3	1	0	3.56	1.04	1.38	.00	2.21	6.28	.56	2.17
Coyote Draw	3	2.62	15	4	1	0	6.91	1.75	3.21	.00	3.58	8.72	.87	3.58
Coyote Draw	2	1.36	3	1	0	0	1.81	1.59	.00	.00	2.27	5.36	.77	1.55
The Gap	2	.96	2	1	0	0	1.26	.95	.00	.00	1.63	4.28	.67	1.63
The Gap	2	1.08	4	1	0	0	2.29	1.25	.00	.00	2.19	5.19	.58	2.07
Coyote Draw	2	1.24	3	1	0	0	2.50	.80	.00	.00	2.04	5.00	.72	1.74
Coyote Draw	3	2.50	11	2	1	0	6.15	1.93	2.08	.00	3.34	7.77	.82	3.27
Saddle Horse Butte	3	.70	5	2	1	0	1.64	1.04	.55	.00	1.50	3.82	.67	1.34
Saddle Horse Butte	2	.40	3	1	0	0	1.25	.60	.00	.00	1.37	3.13	.44	1.03
Saddle Horse Butte	2	1.37	4	1	0	0	2.42	2.41	.00	.00	2.83	6.35	.70	2.59
Neil Butte	2	3.52	3	1	0	0	1.64	1.12	.00	.00	1.54	9.44	1.51	.96
Neil Butte	2	3.70	8	1	0	0	5.86	2.35	.00	.00	2.72	10.1	1.70	2.46
Eagle Rock	3	2.26	8	2	1	0	3.25	3.99	.92	.00	3.29	7.94	.81	3.01
Neil Butte	3	2.14	10	2	1	0	3.22	1.48	2.61	.00	3.56	8.31	.83	3.25
Neil Butte	2	.80	7	1	0	0	1.53	1.05	.00	.00	1.37	4.28	.58	1.18
Neil Butte	2	.80	3	1	0	0	.71	1.80	.00	.00	2.02	4.66	.54	2.02
Neil Butte	3	1.78	9	2	1	0	3.54	1.98	.75	.00	2.32	6.05	1.32	2.10
Neil Butte	2	.82	4	1	0	0	.84	1.92	.00	.00	1.97	4.31	.52	1.84
Reno Reservoir	4	8.84	41	10	3	1	15.7	6.56	6.50	5.17	6.84	14.6	1.78	6.40
Hilight	3	1.98	6	2	1	0	2.27	2.43	.50	0.00	2.29	6.66	1.27	2.21
Hilight	3	3.72	8	2	1	0	3.37	0.66	4.14	.00	4.20	9.97	1.39	3.87
Hilight	2	1.14	6	1	0	0	1.92	2.28	.00	.00	2.15	5.08	.72	2.05
Hilight	3	1.14	6	2	1	0	2.31	.72	1.70	.00	2.18	5.97	.65	2.05
Hilight	3	3.26	14	3	1	0	5.21	3.24	1.74	.00	3.30	9.84	1.10	2.86
Open A Ranch	3	1.60	6	2	1	0	3.04	1.78	.68	.00	2.51	6.75	.76	2.46
The Gap SW	3	1.65	6	2	1	0	2.63	1.83	1.12	.00	2.58	6.49	.99	2.58
Saddle Horse Butte	3	2.86	11	3	1	0	5.03	2.15	2.65	.00	4.19	8.27	1.09	3.11
The Gap SW	2	3.56	3	1	0	0	2.05	3.08	.00	.00	4.40	10.2	1.13	2.85
09221680 (4)	3	8.90	19	5	1	0	19.2	8.19	5.60	.00	6.55	17.5	1.68	6.53
06313180 (5)	2	.71	4	1	0	0	2.15	.84	.00	.00	1.27	4.20	.90	1.14
06312920 (6)	2	1.34	5	1	0	0	3.43	1.31	.00	.00	1.59	5.73	1.27	2.17
06266320 (7)	2	1.30	2	1	0	0	1.74	.07	.00	.00	1.14	5.40	.77	1.09
06256670 (8)	3	5.86	9	2	1	0	9.70	4.05	.25	.00	3.94	12.2	2.37	2.73
06634910 (9)	3	3.01	6	2	1	0	3.67	1.25	1.76	.00	2.98	9.05	2.02	2.94
06266460 (10)	2	2.32	2	1	0	0	4.39	.10	.00	.00	3.05	7.84	1.31	3.03
06644840 (11)	3	2.15	12	2	1	0	6.14	2.01	.55	.00	2.20	5.92	1.18	2.05
06313050 (12)	3	5.44	5	2	1	0	7.38	1.39	.39	.00	2.01	10.4	3.96	2.06
06267260 (13)	4	3.77	17	4	2	1	10.5	3.16	1.02	.16	2.64	9.29	1.60	2.60
06267270 (14)	2	2.11	7	1	0	0	4.39	2.43	.00	.00	2.71	7.35	.94	2.84
06634950 (15)	2	1.98	6	1	0	0	4.00	1.72	.00	.00	2.48	8.25	1.15	2.54
06382200 (16)	3	5.12	11	4	1	0	8.27	3.71	1.75	.00	3.31	10.4	2.64	3.17
06648720 (17)	2	.79	2	1	0	0	2.45	.83	.00	.00	1.80	4.47	.54	1.97
06274190 (18)	3	1.51	19	5	1	0	5.47	2.33	1.07	.00	2.45	6.46	.89	2.59
06233360 (19)	3	8.23	7	2	1	0	7.67	6.25	.47	.00	6.17	15.3	1.85	5.95
06312910 (20)	2	1.53	5	1	0	0	4.40	1.90	.00	.00	2.88	6.72	.97	2.74
06316480 (21)	3	2.99	8	2	1	0	5.20	2.81	.56	.00	3.36	8.98	1.37	3.31
06631150 (22)	3	10.8	17	5	1	0	12.9	4.93	5.99	.00	6.15	18.8	1.78	5.76

[1]Name of U.S. Geological Survey 1:24,000-scale topographic map. Data for these sites are modified from Martin

[2]U.S. Geological Survey streamflow-gaging station number and site number (in parentheses) shown in figure 1.

Channel length (miles)	Basin relief (feet)	Used relief (feet)	Channel slope (foot per foot)	Sinuosity	Relief ratio (feet per mile)	Total channel length (miles)	Drainage density (miles per square mile)	Circularity ratio	Stream frequency (streams per square mile)	Maximum side-slope relief (feet)	Side-slope distance (miles)	Maximum value side-slope (foot per foot)
1.66	314	180	0.030	1.10	189	3.32	4.49	0.506	10.8	180	0.120	0.284
7.09	331	132	.012	1.42	62.6	27.1	3.50	.571	6.2	120	.092	.247
1.42	184	92	017	1.13	130	2.99	3.29	.757	4.4	60	.187	.060
1.72	410	122	.019	1.14	246	2.70	3.81	.541	8.4	180	.137	.248
1.66	375	221	.036	1.20	239	2.50	4.92	.481	7.8	120	.054	.420
3.20	403	220	.018	1.09	137	10.8	3.36	.685	7.7	120	.120	.189
2.68	433	119	.012	1.34	183	9.84	4.65	.551	8.0	90	.096	.177
2.01	284	135	.018	1.08	154	3.05	3.48	.424	5.7	130	.486	.050
2.60	276	120	.013	1.07	99.3	9.70	2.99	.500	4.3	140	.403	.065
2.21	461	139	.017	1.16	209	5.93	3.15	.680	4.7	300	.520	.109
3.87	441	130	.009	1.27	140	9.07	2.65	.614	3.2	140	.300	.088
2.58	232	120	.012	1.12	97.9	4.01	4.33	.447	5.3	180	.428	.079
1.98	194	124	.016	1.17	113	2.70	1.95	.666	4.3	100	.454	.041
8.44	405	148	.004	1.40	64.1	20.2	2.46	.476	2.4	300	1.07	.063
4.42	205	85	.005	1.38	61.7	9.14	3.28	.504	3.2	100	2.31	.008
1.28	205	152	.032	1.06	163	4.49	2.89	.555	4.5	120	.320	.071
1.12	211	140	.033	1.06	192	1.53	3.80	.644	7.4	120	.295	.077
4.69	312	197	.011	1.24	80.2	14.1	4.24	.461	6.3	141	.340	.078
2.35	190	93	.010	1.08	76.6	4.17	1.95	.416	3.7	170	.430	.074
3.18	241	135	.011	1.23	84.3	8.04	3.73	.555	5.1	100	.248	.076
4.14	443	155	.010	1.09	117	12.1	2.90	.509	3.3	100	.237	.079
4.41	379	152	.009	1.21	85.6	14.4	3.22	.353	4.9	125	.353	.067
2.38	289	98	.011	1.12	136	3.48	3.34	.530	3.8	160	.542	.059
2.45	283	136	.015	1.12	128	5.98	4.82	.394	9.6	80	.302	.050
4.70	241	106	.006	1.31	67	11.9	4.53	.432	7.6	202	.697	.054
2.33	176	58	.006	1.50	77.5	3.40	2.50	.594	2.9	80	.349	.043
1.79	231	85	.012	1.09	142	2.21	2.30	.657	3.1	140	.358	.074
2.18	252	78	.009	1.05	115	3.54	3.27	.503	4.6	192	.406	.089
2.03	329	113	.015	1.16	162	3.30	2.66	.622	3.2	100	.423	.044
4.01	320	164	.011	1.22	95.8	10.2	4.06	.520	5.6	160	.484	.062
1.40	222	116	.022	1.04	148	3.23	4.61	.602	11.4	80	.178	.085
1.10	200	74	.018	1.06	146	1.85	4.56	.519	9.8	100	.196	.099
3.10	240	135	.011	1.19	84.8	4.83	3.52	.426	3.6	60	.199	.057
1.38	379	95	.018	1.43	246	2.76	.78	.496	1.1	207	.396	.099
2.92	432	67	.006	1.18	159	8.21	2.21	.459	2.4	145	.393	.069
3.70	429	176	.012	1.22	130	8.16	3.61	.450	1.8	252	.353	.135
4.01	393	130	.008	1.23	110	7.31	3.41	.389	6.0	283	.540	.199
1.31	223	92	.019	1.11	163	2.58	3.21	.550	9.9	80	.190	.079
2.04	134	50	.006	1.00	66.3	2.51	3.15	.459	5.0	80	.230	.065
3.03	254	70	.006	1.44	109	6.27	3.52	.610	6.7	80	.232	.065
2.13	204	92	.009	1.15	104	2.76	3.36	.555	6.0	90	.310	.054
9.67	274	100	.002	1.51	40.1	33.9	3.83	.523	6.2	120	.530	.042
2.60	191	107	.011	1.17	83.4	5.20	2.62	.560	4.5	100	.234	.080
5.00	390	210	.011	1.29	92.9	8.17	2.19	.470	2.9	217	.619	.066
2.43	276	172	.019	1.18	128	4.20	3.68	.554	6.1	110	.509	.040
2.53	165	89	.009	1.23	75.7	4.73	4.14	.401	7.8	190	.267	.134
3.65	232	156	.011	1.27	70.3	10.2	3.12	.422	5.5	110	.425	.049
2.76	259	125	.012	1.12	103	5.50	3.43	.441	5.6	200	.283	.133
2.96	296	160	.014	1.14	115	5.58	3.38	.492	5.45	150	.280	.101
4.19	342	132	.008	1.34	81.6	9.88	3.45	.525	5.24	110	.065	.320
3.17	402	112	.009	1.11	91.4	5.13	1.44	.432	1.12	230	.820	.053
9.37	594	440	.012	1.44	90.7	33.0	3.71	.366	2.8	240	.170	.267
1.20	191	120	.040	1.05	150	2.98	4.20	.480	7.0	50	.061	.155
2.18	210	98	.012	1.00	132	4.74	3.54	.513	4.5	50	.077	.123
1.15	140	80	.022	1.06	122	1.81	1.40	.560	2.33	160	.200	.152
3.01	220	267	.015	1.10	55.8	14.0	2.39	1.03	2.0	130	.067	.369
3.35	438	320	.026	1.14	147	6.69	2.22	.462	3.0	170	.105	.307
3.17	457	417	.025	1.05	150	4.49	1.89	.474	.9	90	.152	.113
2.15	220	130	.016	1.05	100	8.70	4.05	.771	7.0	120	.165	.138
2.34	150	190	.021	1.14	74.8	9.15	1.68	.628	1.5	110	.114	.183
2.71	186	120	.012	1.04	70.5	14.8	3.93	.549	6.6	95	.063	.286
3.20	285	170	.014	1.13	105	6.82	3.23	.492	3.8	90	.031	.543
2.65	517	335	.034	1.04	209	5.72	2.89	.366	3.5	140	.066	.402
3.43	263	115	.007	1.08	79.4	13.7	2.68	.590	3.1	120	.106	.214
2.08	338	189	.024	1.06	188	3.28	2.64	.498	3.8	70	.173	.077
2.67	382	116	.012	1.03	156	8.87	5.87	.454	16.6	125	.063	.378
6.97	448	315	.012	1.17	72.6	14.4	1.75	.441	1.2	105	.135	.147
2.98	297	140	.012	1.09	103	6.30	4.12	.426	3.9	48	.058	.157
3.36	345	235	.019	1.01	103	8.57	2.88	.463	3.7	135	.073	.350
6.65	483	302	.012	1.16	78.6	23.8	2.20	.384	2.8	148	.171	.164

and others (1988, p. 124-130).

Data for these sites are modified and expanded from Craig and Rankl (1978, p. 25).

Table 4.--Statistical properties for first-order drainage basins

[Number of basins in sample = 54 (table 2)]

Characteristic	Minimum	Maximum	Arithmetic mean	Geometric mean	Standard deviation of arithmetic values
Drainage area (square miles)	0.04	1.85	0.25	0.18	0.30
Basin length (miles)	.32	2.52	.83	.76	.40
Basin perimeter (miles)	.85	6.45	2.22	2.03	1.06
Valley length (miles)	.22	2.39	.67	.61	.36
Channel length (miles)	.22	2.60	.72	.65	.39
Basin relief (feet)	45.0	335	144	131	63.9
Used relief (feet)	25.0	240	85.8	75.1	45.2
Channel slope (foot per foot)	.009	.054	.025	.022	.013
Sinuosity	1.00	1.28	1.06	1.06	.06
Relief ratio (feet per mile)	55.9	502	198	173	107
Total channel length (miles)	.22	2.60	.72	.65	.39
Drainage density (miles per square mile)	1.06	9.66	4.11	3.70	1.91
Circularity ratio	.277	.843	.549	.533	.134
Maximum value sideslope (foot per foot)	.014	.293	.080	.065	.058

The physical characteristics of drainage networks commonly are interrelated. For example, as drainage area increases, the number of stream channels and the order of the main stream channel also increase. To determine those variables for which significant interrelations might exist, a correlation analysis was made (table 8). These correlations were used as a guide to develop graphs (figs. 8-10) and regression relations (table 9) for the physical characteristics that are significantly related and that are considered important in drainage-basin stability and geomorphic design.

Additional Design Considerations

The previous sections present data and equations that can be used as guides to design characteristics of drainage basins and stream channels disturbed by development that are similar to those of undisturbed, natural drainage basins and stream channels. However, additional criteria also need to be considered and are described in the following sections.

Table 5.--Statistical properties for second-order drainage basins

[Number of basins in sample = 29 (table 3)]

Characteristic	Minimum	Maximum	Arithmetic mean	Geometric mean	Standard deviation of arithmetic values
Drainage area (square miles)	0.40	3.70	1.37	1.16	0.88
Basin length (miles)	1.10	4.40	2.02	1.65	.71
Basin perimeter (miles)	2.80	10.2	5.59	5.31	1.92
Basin width (miles)	.41	1.70	.81	.75	.33
Valley length (miles)	.96	3.03	1.86	1.76	.62
Channel length (miles)	1.10	3.20	2.09	1.98	.67
Basin relief (feet)	134	517	277	261	98.5
Used relief (feet)	50.0	417	132	118	77.6
Channel slope (foot per foot)	.006	.040	.018	.016	.009
Sinuosity	1.00	1.50	1.13	1.12	.11
Relief ratio (feet per mile)	66.3	246	144	136	47.8
Total channel length (miles)	1.53	8.21	3.70	3.42	1.56
Drainage density (miles per square mile)	.78	4.92	3.08	2.89	.97
Circularity ratio	.366	.757	.523	.516	.086
Stream frequency (streams per square mile)	.90	9.90	4.67	4.04	2.34
Maximum sideslope relief (feet)	48.0	230	116	106	49.1
Sideslope distance (miles)	.031	.820	.283	.218	.18
Maximum value sideslope (foot per foot)	.041	.543	.077	.092	.13

Environmental Regulations

The restoration of mined land to its approximate original contour is a requirement of the Surface Mining Control and Reclamation Act of 1977 (U.S. Congress, 1977). In some coal areas of Wyoming, however, the thick coal beds and small overburden-to-coal ratio prevent restoring the landscape to its former elevation (Keefer and Hadley, 1976, p. 15-20). As discussed by Toy and Hadley (1987, p. 276), it generally is agreed that "approximate original contour," as required by law, means that the shape of the land after mining should be about the same as it was before mining, but not necessarily at the same elevation.

Table 6.--Statistical properties for third-order drainage basins

[Number of basins in sample = 35 (table 3)]

Characteristic	Minimum	Maximum	Arithmetic mean	Geometric mean	Standard deviation of arithmetic values
Drainage area (square miles)	0.70	10.8	3.22	2.64	2.30
Basin length (miles)	1.50	6.55	3.20	3.01	1.20
Basin perimeter (miles)	3.82	18.8	8.69	8.19	3.27
Basin width (miles)	.47	3.96	1.27	1.14	.69
Valley length (miles)	1.34	6.53	2.98	2.79	1.17
Channel length (miles)	1.40	9.37	3.32	3.59	1.60
Basin relief (feet)	150	594	320	302	108
Used relief (feet)	70.0	440	166	152	80.5
Channel slope (foot per foot)	.005	.303	.013	.012	.006
Sinuosity	1.01	1.44	1.19	1.18	.12
Relief ratio (feet per mile)	55.8	209	106	100	37.8
Total channel length (miles)	3.23	33.0	9.66	8.52	5.74
Drainage density (miles per square mile)	1.68	5.87	3.36	3.22	.98
Circularity ratio	.366	1.03	.518	.505	.12
Stream frequency (streams per square mile)	1.20	16.6	5.35	4.55	3.22
Maximum sideslope relief (feet)	80.0	300	149	140	57.8
Sideslope distance (miles)	.063	2.31	.327	.231	.39
Maximum value sideslope (foot per foot)	.008	.378	.150	.116	.10

An additional requirement of the Surface Mining Control and Reclamation Act of 1977 (U.S. Congress, 1977) is 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 basically requires that procedures during mining and reclamation minimize the contribution of suspended materials outside the lease boundaries, control rilling and gullying, and minimize disturbance to the prevailing hydrologic balance.

Surface coal mines in thick coal beds commonly are exempt from the strict requirement of restoring the land to the "approximate original contour" because they are classified as having "thin overburden." This classification

Table 7.--Statistical properties for fourth-order drainage basins

[Number of basins in sample = 6 (table 3)]

Characteristic	Minimum	Maximum	Arith-metic mean	Geo-metric mean	Standard deviation of arithmetic values
Drainage area (square miles)	3.22	8.84	6.03	5.58	2.49
Basin length (miles)	2.64	6.84	4.75	4.46	1.73
Basin perimeter (miles)	7.68	14.7	12.0	11.7	2.87
Basin width (miles)	1.31	1.97	1.69	1.67	.25
Valley length (miles)	2.60	6.40	4.42	4.17	1.61
Channel length (miles)	2.71	9.67	5.92	5.30	2.89
Basin relief (feet)	186	405	330	318	86.3
Used relief (feet)	100	220	145	141	41.2
Channel slope (foot per foot)	.002	.018	.010	.008	.006
Sinuosity	1.04	1.51	1.28	1.27	.19
Relief ratio (feet per mile)	40.1	137	76.6	71.4	33.0
Total channel length (miles)	10.8	33.9	20.2	18.7	8.79
Drainage density (miles per square mile)	2.46	3.83	3.38	3.34	.53
Circularity ratio	.353	.685	.526	.516	.11
Stream frequency (streams per square mile)	2.40	7.70	5.67	5.33	1.84
Maximum sideslope relief (feet)	95.0	300	147	135	75.9
Sideslope distance (miles)	.063	1.07	.371	.228	.39
Maximum value sideslope (foot per foot)	.042	.286	.149	.115	.11

is applied when the thickness of the coal is large, relative to the overburden. Adequate drainage still is required, but the reclaimed landscape can be more subdued than it was before mining.

The Wyoming Environmental Quality Act (Wyoming State Legislature, 1973) requires that each operator of a surface coal mine provide a plan to minimize disturbances to the prevailing hydrologic balance at the mine site and in adjacent areas, and to protect the quantity and quality of water in ground- and surface-water systems during and after mining. Hydrology guidelines prepared by the Wyoming Department of Environmental Quality (1990b) recommend that coal-mining companies measure various drainage basin and stream channel

Table 8.--Summary of correlation analysis of physical characteristics for drainage basins

[Values listed are correlation coefficients; analysis made using logarithms of characteristics]

	Drainage area	Basin length	Basin perimeter	Basin width	Valley length	Channel length	Basin relief	Used relief	Channel slope	Sinuosity	Relief ratio	Total channel length	Drainage density	Circularity ratio	Stream frequency	Maximum sideslope relief	Sideslope distance	Maximum value sideslope
Drainage area	1.00																	
Basin length	.96	1.00																
Basin perimeter	.99	.97	1.00															
Basin width	.92	.70	.85	1.00														
Valley length	.95	.98	.96	.65	1.00													
Channel length	.95	.98	.96	.70	.99	1.00												
Basin relief	.71	.73	.72	.44	.75	.75	1.00											
Used relief	.57	.60	.59	.14	.65	.63	.77	1.00										
Channel slope	-.62	-.65	-.62	.51	-.68	-.63	-.17	.16	1.00									
Sinuosity	.57	.58	.56	.57	.54	.62	.43	.23	-.56	1.00								
Relief ratio	-.64	-.67	-.64	-.38	-.63	-.64	.01	.05	.78	-.39	1.00							
Total channel length	.96	.97	.97	.78	.98	.98	.75	.56	-.65	.72	-.60	1.00						
Drainage density	-.50	-.34	-.46	-.42	-.29	-.29	-.16	-.05	.33	-.17	.34	-.24	1.00					
Circularity ratio	-.11	-.27	-.24	.06	-.26	-.25	-.22	-.23	.11	-.08	.16	-.20	-.18	1.00				
Stream frequency	-.53	-.45	-.52	-.47	-.40	-.41	-.23	-.04	.50	-.34	.41	-.33	.84	.00	1.00			
Maximum sideslope relief	.29	.26	.29	.16	.30	.27	.41	.51	.19	.00	.06	.20	.02	-.01	-.26	1.00		
Sideslope distance	.30	.29	.33	.20	.30	.29	-.06	-.13	-.45	.12	-.35	.16	-.35	-.23	-.50	.38	1.00	
Maximum value sideslope	.10	.10	.09	-.10	.12	.12	.34	.39	.25	.06	.22	.15	.13	.03	.17	.27	-.78	1.00

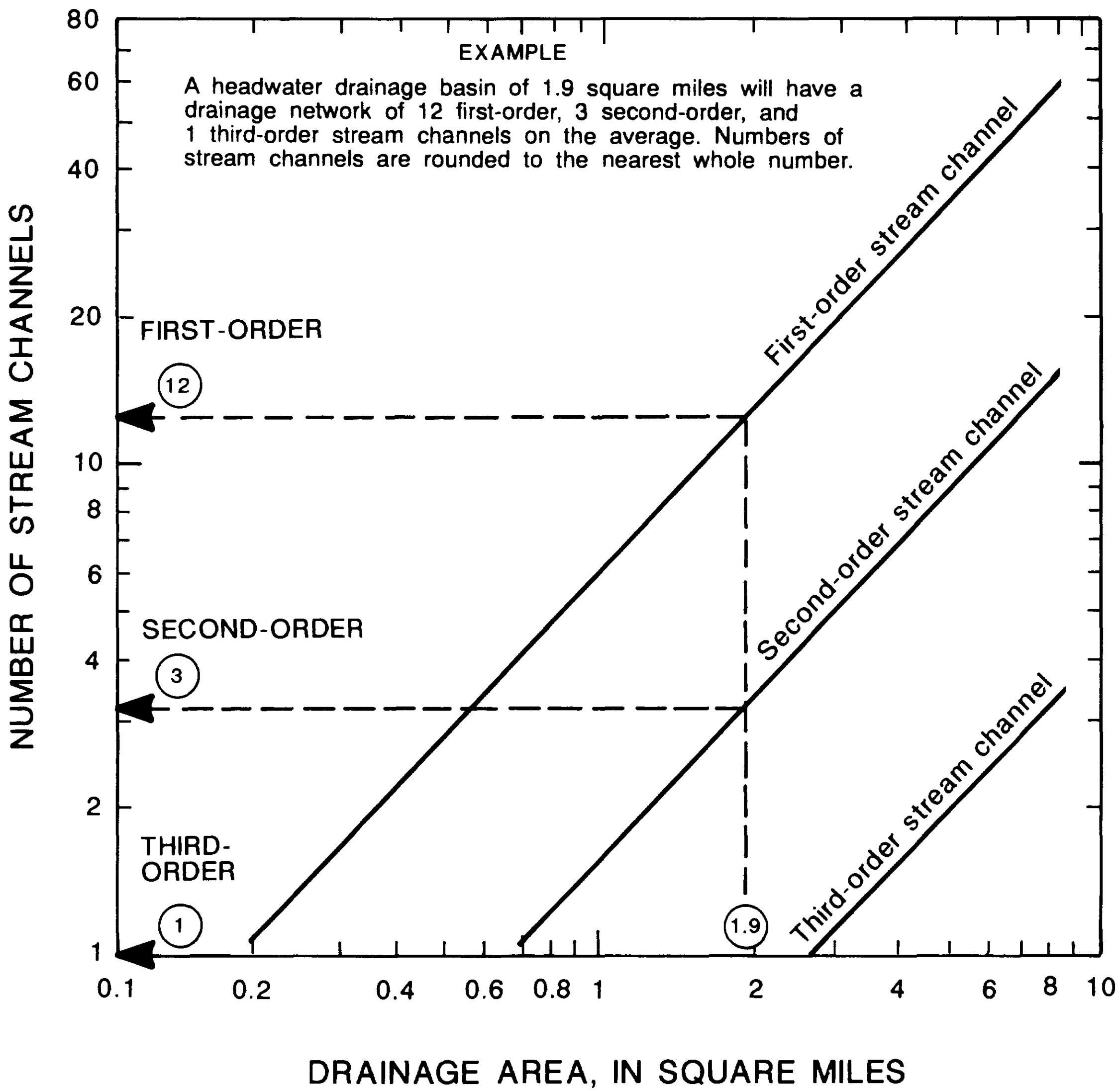


Figure 9.--Relations of number of first-, second-, and third-order stream channels to drainage area.

Drainage Density

A comprehensive study of the determination of drainage density for three small surface-mine reclamation areas in the western United States was made by Gregory and others (1985). Their study included the measurement of drainage density for 69 natural drainage basins near the Dave Johnston and Jim Bridger Coal Mines in Wyoming (fig. 1), and the McKinley Coal Mine in New Mexico. They note that drainage density is a geomorphic variable that integrates effects of other basin characteristics. They suggest that if the optimum density is restored, the adjustment of the stream network for a reclaimed area

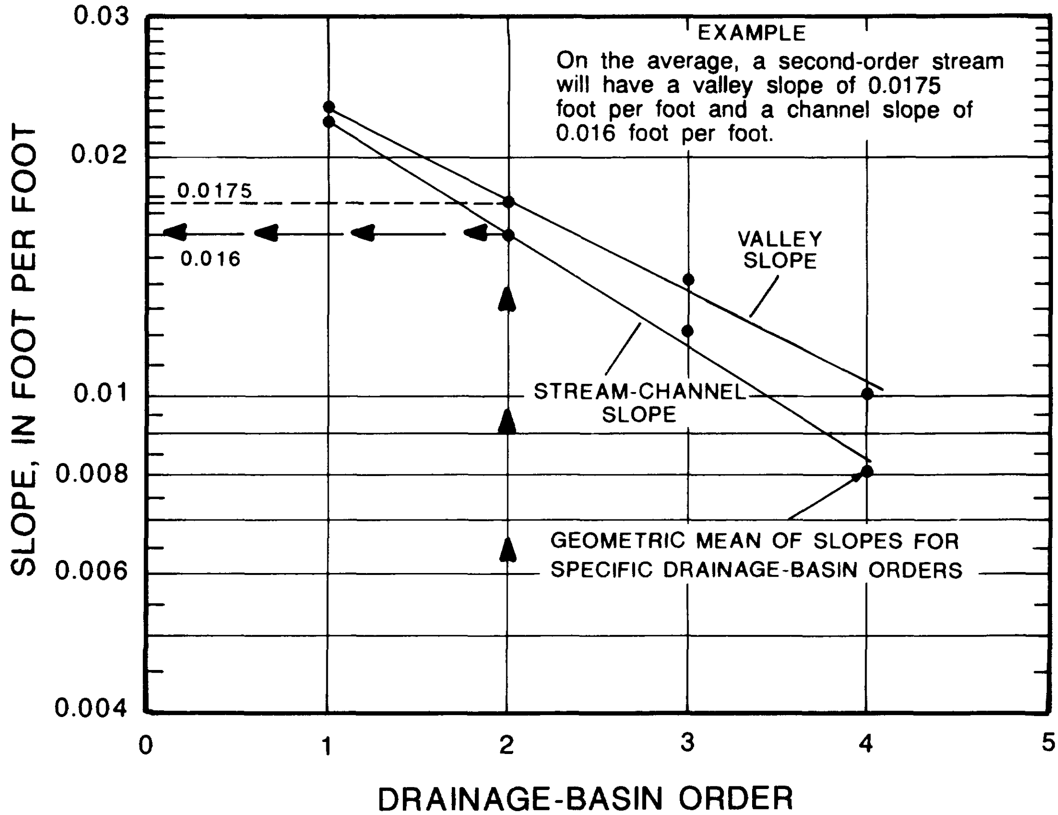


Figure 10.--Relations of valley and stream-channel slopes to drainage-basin order.

should be minimal. Gregory and others (1985, p. 1) conclude "There is a characteristic drainage density for each location, and when this is identified, it should be used in reclamation design." They also note, however, that (1) surface coal mining and reclamation will change properties of the natural drainage basin that will affect drainage density; (2) characteristic drainage densities used for design will require adjustment as a result of such changes; and (3) additional research is needed in order to refine estimates of drainage density.

Schaefer and others (1979) suggested that postmining drainage density could be estimated using measurements of the premining natural drainage basins and aerial photographs, and then the drainage density could be increased to account for the effects of disruption. Conversely, Stiller and others (1980) note that reconstructing a drainage basin with a greater drainage density than the natural drainage density could create additional hydrologic effects such as increased magnitude of flood peaks. They suggest reclaiming with a reconstructed drainage density at least equal to the premining drainage density.

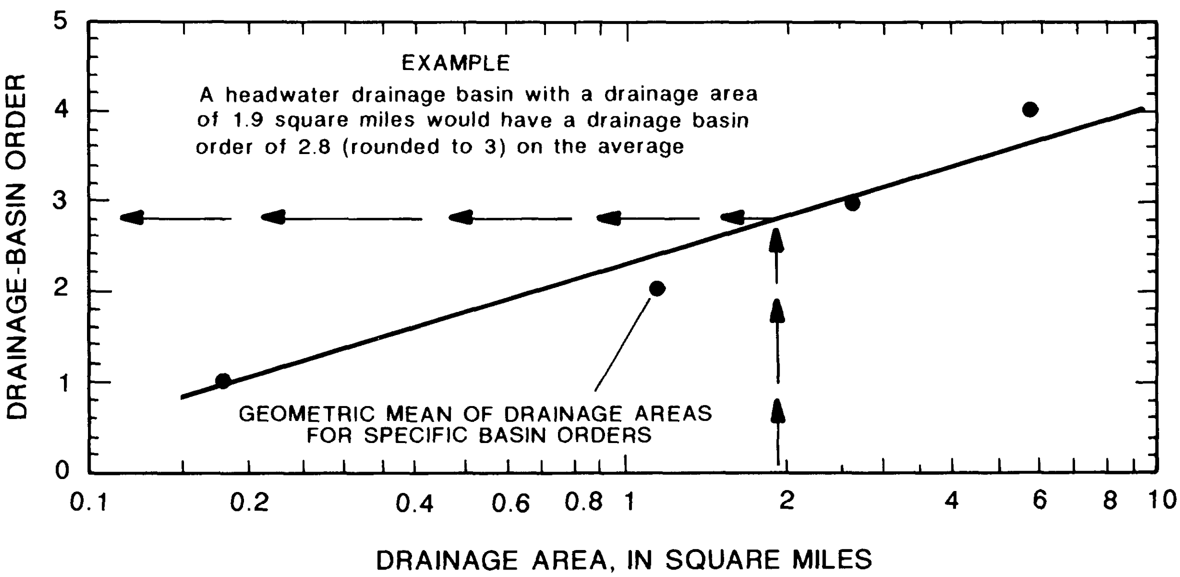


Figure 8.--Relation of drainage-basin order to drainage area.

characteristics to aid in the reclamation of surface-drainage systems. Mine plans on file with the Wyoming Department of Environmental Quality contain these data and also document the procedures used or planned for reclamation of stream channels and drainage networks. In addition, numerous studies and guidelines for design criteria have been made by hydrologists working with the mining companies and State and Federal agencies. (See for example: articles by Bergstrom (1985), Harvey and others (1985), and Kearney (1985), published in proceedings of the "Second Hydrology Symposium on Surface Coal Mining in the Northern Great Plains;" Knutson (1982), Lidstone (1982), and Tarquin and Baeder (1982), published in proceedings of the "Hydrology Symposium on Surface Coal Mines in the Powder River Basin;" and Divis and Tarquin (1981)).

Stream Channel and Valley Slopes

The slope of a stream channel affects stability. Unstable stream channels resulting from rapid velocities and erosion of streambeds and banks are most likely to occur in reaches with steep gradients.

The sinuosity and slope of a stream channel are affected by valley slope (Schumm, 1977, p. 137-149). During the design process, valley slope needs to be determined first (fig. 10). The sinuosity of a reconstructed stream channel then can be selected to dictate appropriate stream-channel distance and slope to achieve nonerosive velocities.

Table 9.--Summary of regression analysis

[BL, basin length, in miles; AREA, drainage area, in square miles; RELIEF, basin relief, in feet; UR, used relief, in feet; CHAN-L, channel length of the dominant stream channel, in miles; CHAN-S, channel slope, in foot per foot; see table 1 for complete description of the characteristics]

Equation number	Regression equation	Correlation coefficient (R)	Standard error of estimate (SE) Log units	Standard error of estimate (SE) Average (percent)
(1)	$BL = 1.81\ AREA^{0.49}$	0.96	0.095	22
(2)	$RELIEF = 224\ AREA^{0.27}$	.70	.169	40
(3)	$RELIEF = 162\ BL^{0.54}$	.73	.162	38
(4)	$UR = 1.57\ RELIEF^{0.79}$	.77	.156	37
(5)	$CHAN\text{-}L = 0.92\ BL^{1.15}$	.98	.065	15
(6)	$CHAN\text{-}S = 0.00033\ BL^{-0.94}UR^{0.92}$	.95	.077	18

A well-developed drainage network promotes efficient drainage, resulting in a short runoff time with a correspondingly large peak flow. Because of the interrelations of various drainage-basin features on drainage density, the design of the optimum density that will result in the most stable landscape is complex.

Zimpfer and others (1982, p. 3) describe studies conducted at the Rainfall-Erosion Facility (REF) that was built at Colorado State University to examine the erosional development of drainage networks and other phenomena of drainage-basin evolution. On the basis of results of studies using the REF, Zimpfer and others (1982, p. 11) concluded that it might not be necessary to re-establish first-order stream channels in a reconstructed drainage basin. They determined that first-order stream channels eventually would form, but that sediment yields from a drainage basin with only the larger-order stream channels would be less than yields from a fully reconstructed drainage basin with first-order stream channels.

As discussed by Chorley and others (1984, p. 257-258), drainage density is interrelated with the angle and length of hillslopes. A substantial drainage density can result in closer stream spacing and steeper valley hillslopes than would result for a minimal drainage density. The degree of basin relief also can influence the valley hillslope. The effects of drainage density and relief on hillslopes are shown in figure 11. Steep hillslopes usually contribute a large quantity of sediment to stream channels; the stream channels also must be steep to transport the sediment.

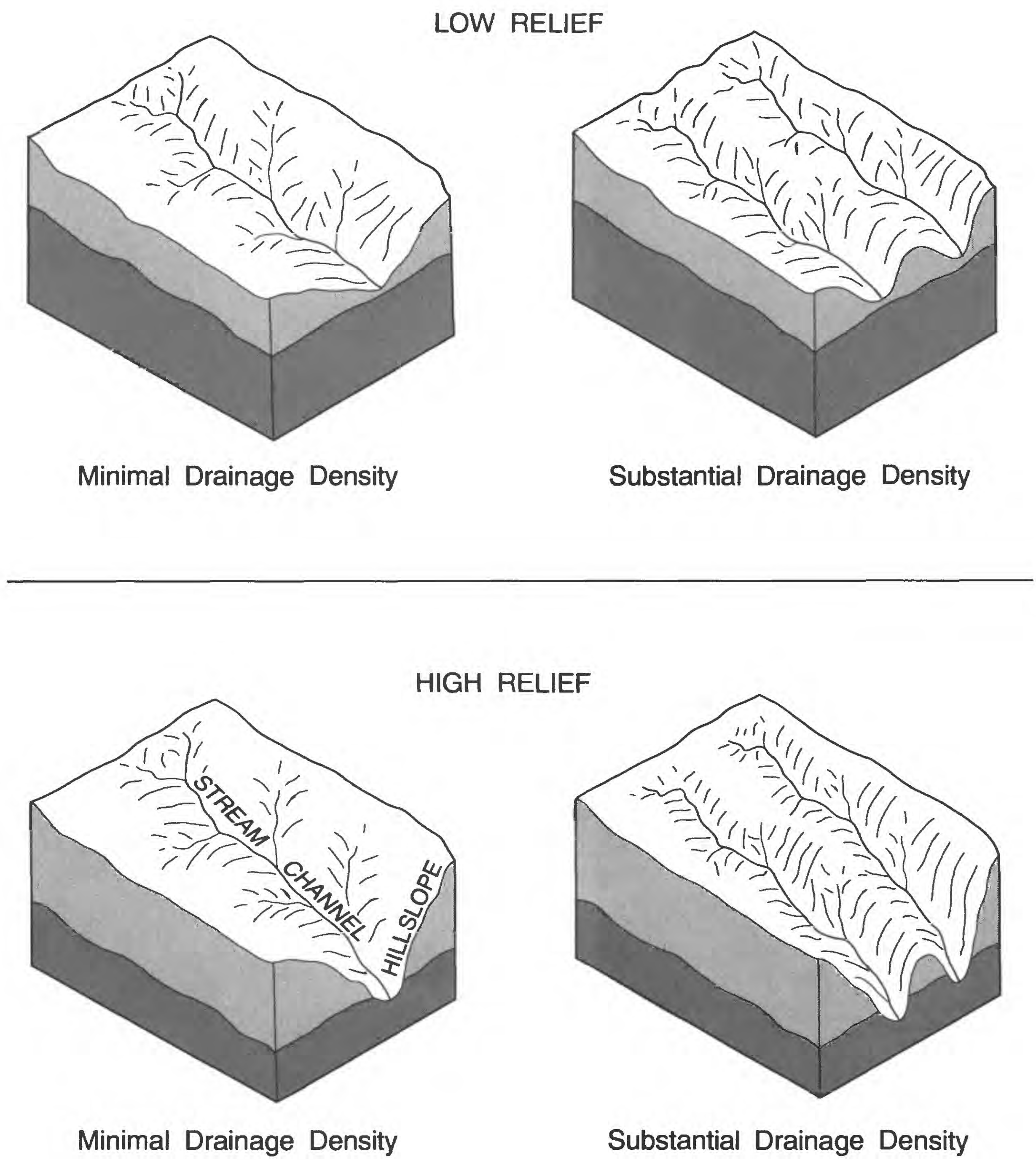


Figure 11.--Effects of drainage density and relief on the angle and length of hillslopes.

Although headcuts and gullys characterize stream channels where erosion is occurring, surface erosion on unrilled slopes yielded 98 percent of the total sediment in a semiarid area of New Mexico (Leopold and others, 1966, p. 239). Likewise, Rankl (1987, p. 15) made detailed measurements of a tributary of Dugout Creek, a semiarid basin in Wyoming with active headcuts. He determined that sediment contribution of the headcuts was a relatively minor part of the total sediment yield from the drainage basin. Steep hill-slopes have overland flows with rapid velocities, which contribute to sediment yield. Provided other characteristics are equal, drainage basins that are designed and reconstructed with lesser drainage densities and correspondingly flatter valley hillslopes will have smaller sediment yields.

Stream-channel reaches where erosion and deposition occur are readily visible. Erosion of topsoil, increased sediment loads, and destruction of vegetation will occur locally as first-order stream channels are reestablished and as the drainage network evolves. However, on the basis of results of the laboratory and field studies described previously (Zimpfer and others, 1982; Leopold and others, 1966; Rankl, 1987), reclamation of drainage basins to simulate an early state of erosional development (with no reconstructed first-order stream channels) would improve overall re-vegetation success and result in lesser annual sediment yield from the drainage basin.

Therefore, reconstruction procedures using somewhat lesser drainage densities than occur naturally could improve revegetation success and decrease sedimentation problems. This conclusion is based on limited laboratory data and on onsite studies of natural drainage basins; additional laboratory and onsite studies of reclaimed drainage basins are needed to verify optimum drainage patterns and densities.

Erosion

The erosion of drainage basins over time can be analyzed through the use of a hypsometric analysis. A hypsometric curve provides a quantitative description of the distribution of material within a drainage basin from the base, or low point of the basin, to the top, or high point of the basin (Strahler, 1952, 1964). For example, a hypsometric analysis was made for second- and higher order drainage basins in northeastern Wyoming (Martin and others, 1988, p. 141-144). The average hypsometric curve for the respective drainage-basin order is shown in figure 12. The curves indicate the proportion of total area that exists at various elevations (expressed as percentage of relief) within the drainage basin from measurements of the area between successive land-surface contours on a topographic map. The square in which the curves are plotted can be visualized as a vertical section through the mass of material that will be removed as the drainage basin evolves (Schumm, 1977, p. 68-69). The right-bottom of the graph is the locus of points of junction of the respective stream channels with a higher order stream. The left-top of the graph represents the drainage divide.

During erosion of a drainage basin, the shape of the hypsometric curve will change from convex upward to virtually straight and then to concave upward (Schumm, 1977, p. 70). Such changes indicate that the zone of maximum erosion migrates with time toward the high point of the drainage divide. The concave shape of the hypsometric curves for all three drainage-basin orders in figure 12 indicates the basins have reached a state in their geomorphic development in which further development will be slow.

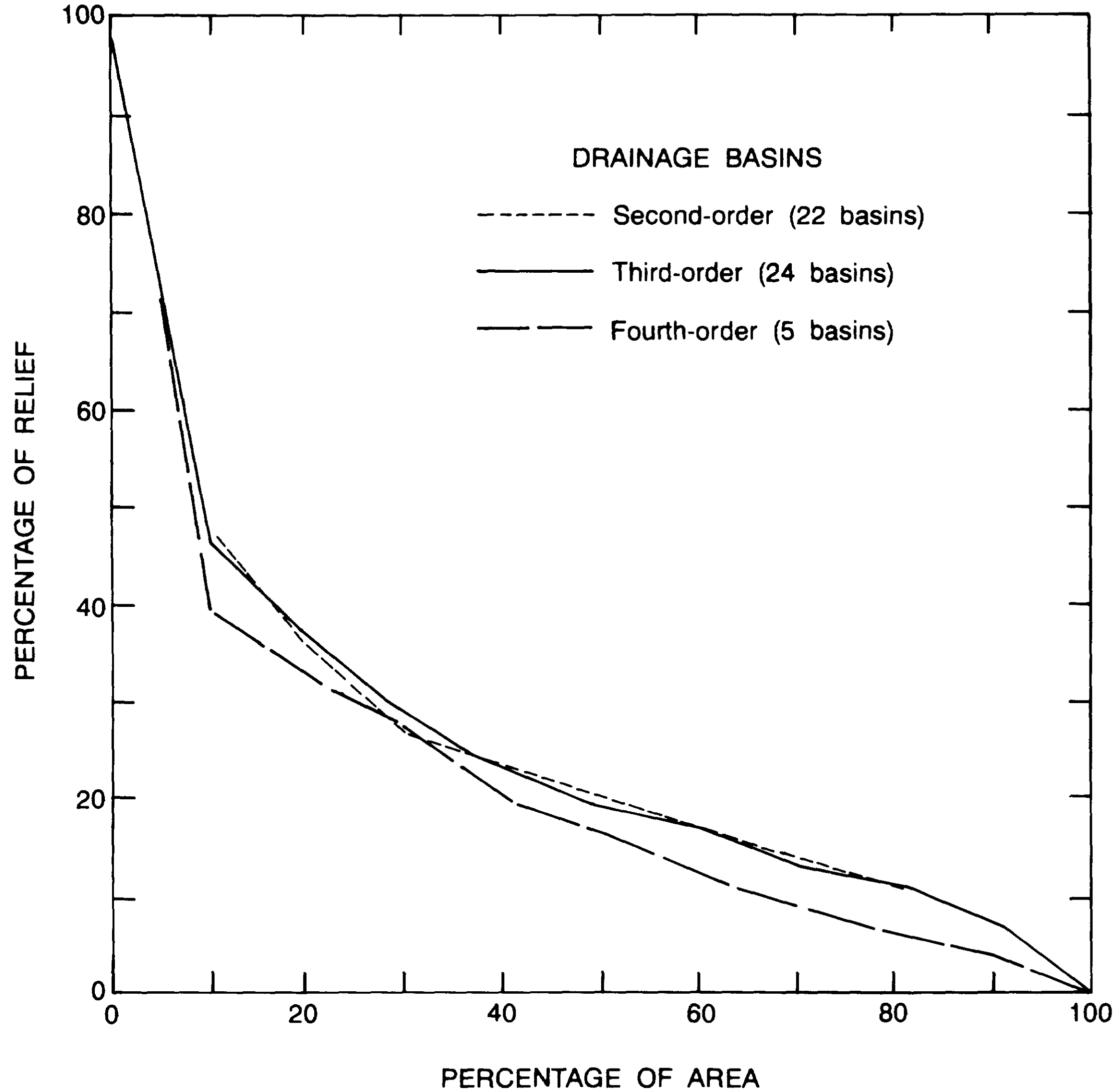


Figure 12.--Average hypsometric curves for second-, third-, and fourth-order drainage basins.

The results of a hypsometric analysis for natural drainage basins, as shown by the example of figure 12, can be used in conjunction with drainage density for comparing the distribution of material and drainage density planned for reconstructed basins. Parker (1977) reported that drainage density of a natural basin increases toward the headwater areas as a drainage basin evolves. If a drainage basin is reclaimed with only the second- and higher order stream channels reconstructed, the drainage network will be similar to that of a natural drainage basin in an early stage of development. Additional development of stream channels is likely to occur; however, the rates of erosion and corresponding sediment yield will not necessarily be larger than if the drainage network was fully reconstructed to include the first-order stream channels.

End-of-Mine Highwalls

A concern with reclamation of large surface mines is that of dealing with end-of-mine highwalls where they intercept stream channels. Small drainage basins located just outside the highwall perimeter, but draining into the mined area, have potential to cause accelerated erosion and unstable stream channels. For example, two small drainage basins that need to be reconstructed are shown by the sketch in figure 13. If the stream channels are constructed without artificial structures or other innovative features, such as storage and recharge areas to capture flow from the small drainage basins, then a large quantity of material will have to be moved and shaped to achieve stable stream-channel slopes in the vicinity of the highwall. In cases where thick coal beds are being removed, an insufficient volume of overburden will be available for reconstruction, and material will need to be taken from unmined areas. In addition to being extremely expensive, the disturbance of an unmined area for the purposes of providing material to a reclaimed mined area could create another disturbed area in need of reclamation.

Stream Channels

For the subsequent discussion of the geomorphic design of stream channels, the drainage basin characteristics, including valley slope, are assumed known. Because valley slope is a primary control for channel slope and sinuosity, successful channel reconstruction will depend greatly on the proper reconstruction of the valley floor (Harvey and others, 1985).

Characteristics of Natural Stream Channels

Geomorphic analysis for stream-channel design involves the evaluation of variables that define the channel shape and dimensions (as depicted in cross-sectional view) and the channel pattern (as depicted in plan view). Channel cross-sectional and pattern variables can be related to each other in terms of a hydraulically and morphologically significant flow known as the formative discharge. For channel design, the analysis of cross-section and pattern variables should reflect, to the extent possible, conditions of this formative discharge.

Formative discharge and the bankfull channel

Channel formation takes place mainly during floodflows when a stream has tremendous energy and is transporting large amounts of sediment. Erosion and deposition occur as the stream sculptures its channel to a size large enough to accommodate most of its flows. Although a range of streamflows probably contributes to channel formation, investigators usually define the formative discharge of a stream as the level of streamflow that just fills the banks of the channel. The channel that contains the formative discharge is called the bankfull channel and the streamflow itself is called the bankfull discharge.

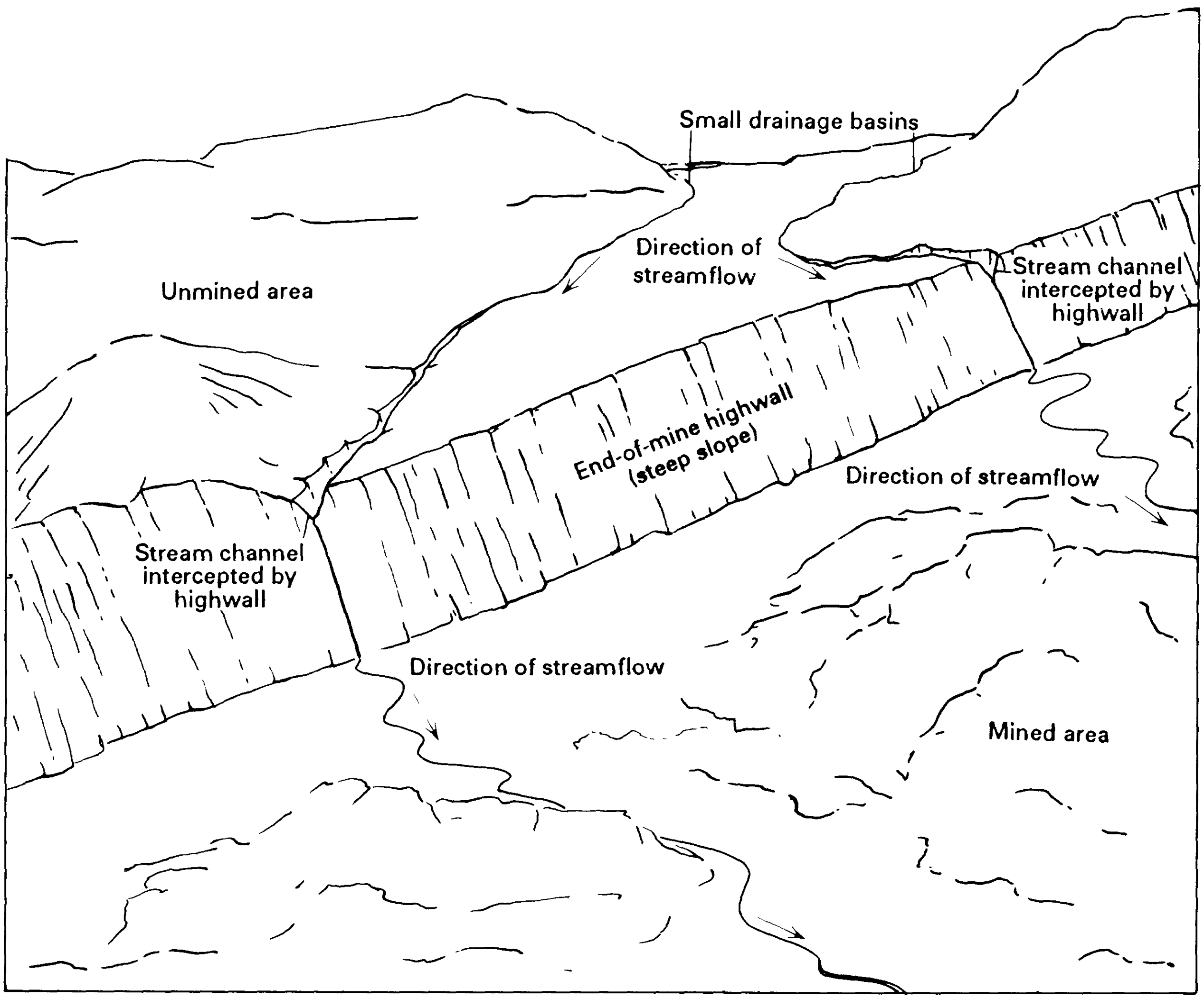


Figure 13.--Example of small stream channels intercepted by strip-mining operation. (A large amount of material will have to be moved and shaped to achieve stable stream-channel slopes in the vicinity of the highwall.)

Numerous criteria have been suggested for defining the bankfull channel and corresponding bankfull discharge. Williams (1978, p. 1142) reviewed 11 criteria that have been used to define the bankfull channel, such as active flood plain, valley flat, and lower limit of perennial vegetation, and discussed methods for evaluating the bankfull discharge. He noted that for geomorphic analysis of stream channels, the banks of the active flood plain are the most significant indicator of the level of bankfull discharge. This criterion was first proposed by Wolman and Leopold (1957).

When detailed onsite investigations of streamflow and channel morphology are not feasible, or perhaps not possible, a statistical definition of bankfull discharge is useful. Most investigators have reported bankfull discharges, based on flow-frequency analysis, ranging from the 1- to 2-year peak flow (Williams, 1978, p. 1143). Wolman and Leopold (1957, p. 88-89) determined that bankfull discharges were described best by a recurrence interval of 1 to 2 years. Lowham (1982, p. 20-24) identified bankfull discharges in the Green River basin of Wyoming as those with an average recurrence interval of about 2 years. For this report, the 2-year annual peak flow (P_2) is used as an index of formative, bankfull discharge for geomorphic analysis.

Channel width and depth

Estimates of channel width and depth are needed for design and reconstruction. Width is defined in this report as the surface width of the bankfull channel. Mean depth of flow is determined as the cross-sectional area of the bankfull channel divided by the width. These channel properties are illustrated in figure 14. Two methods for defining cross-sectional channel shape are described and used in this study: (1) the channel-geometry method (Lowham, 1988, p. 21-26); and (2) hydraulic-geometry relations (Leopold and Maddock, 1953, p. 9-16). Because only the maximum cross-sectional channel depth was measured by Lowham (1988), estimates of mean depth were developed only for hydraulic-geometry relations.

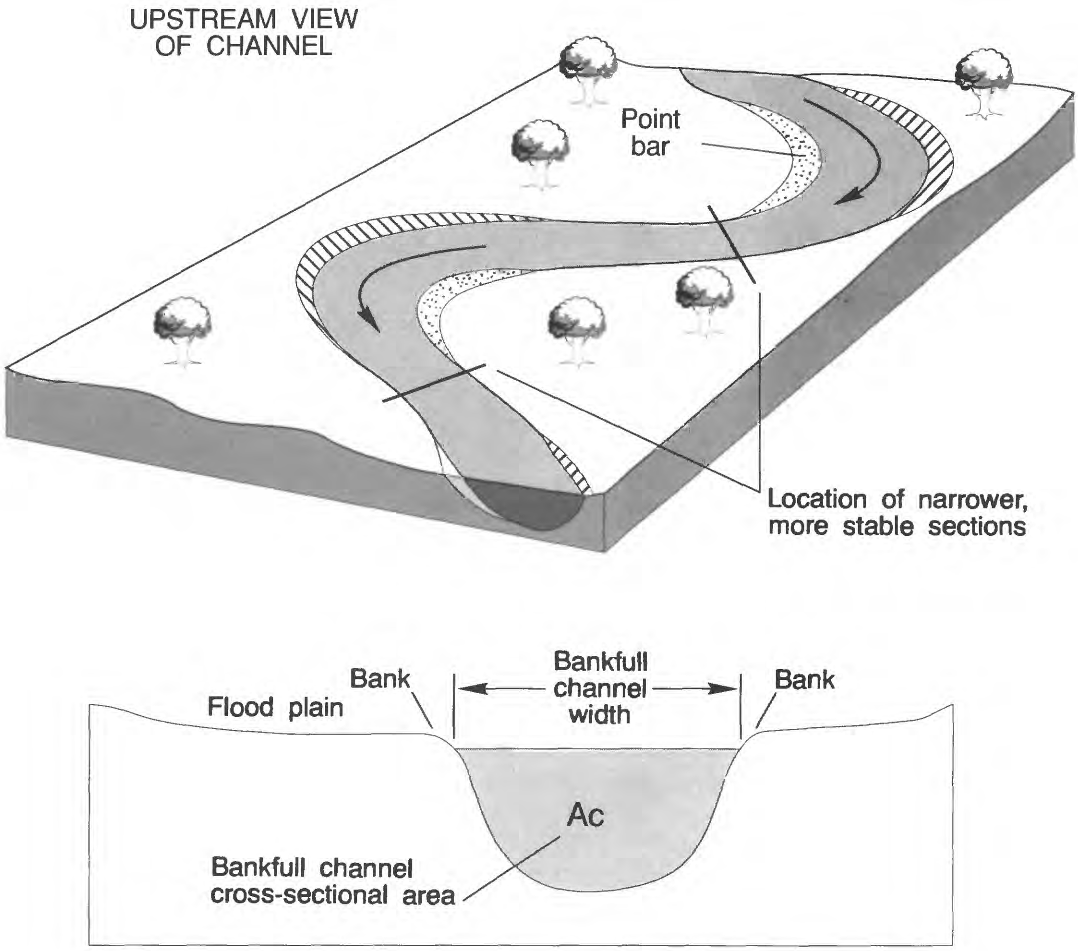
Channel-geometry method.--The channel-geometry method is based on the relation between the size of a natural channel and the magnitude of streamflow. Large streamflows create large channels; smaller streamflows create smaller channels. Using this concept, Lowham (1988) measured the bankfull width of streams in the study area, and developed empirical relations for estimating peak discharge and annual runoff at ungaged sites using width measurements. In this method, the width measurement is made at the narrowest section of a straight, stable reach, which generally is located just downstream from a bend. The location of such measurement sections is shown in figure 14.

Hydraulic-geometry relations.--Leopold and Maddock (1953) introduced the concept of hydraulic geometry for alluvial streams. The authors developed equations relating hydraulic properties at a cross section to stream discharge. These at-a-station relations have the general form:

$$X = aQ^b \tag{7}$$

where X is the cross-sectional hydraulic property of interest;
Q is discharge;
a is an empirically derived constant; and
b is an empirically derived slope coefficient.

Values for a and b (eq. 7) are derived empirically for a range of discharges at a particular stream cross section.



$$D = Ac / W$$

Where D = mean depth of flow, in feet
Ac = cross-sectional area of bankfull channel, in square feet
W = surface width of bankfull channel, in feet

Figure 14.--Cross-sectional properties of a channel at bankfull flow.

When a given discharge, such as bankfull or mean-annual discharge, is used in equation 7, cross-sectional properties of one stream can be related to those of another stream. Average values for the derived constants and slope coefficients were presented by Leopold and Maddock (1953, p. 2-19) for the streams they studied. These so-called regional (or downstream) relations can differ considerably depending on stream type, regional geography, climate, and surface geology.

Using data from current-meter measurements of discharge at streamflow-gaging stations, Lowham (1982, p. 26-38) developed hydraulic-geometry relations for bankfull discharge of streams in the Green River basin of Wyoming. Apley (1976) developed hydraulic-geometry relations for ephemeral and intermittent streams in the Powder River basin of Wyoming; however, his relations were based on mean-annual discharge, which generally is much smaller than bankfull discharge. In this study, channel cross-sectional properties at streamflow-gaging stations were used to develop hydraulic-geometry relations for the plains and high desert regions.

Channel pattern

The patterns of natural streams generally are described as straight, braided, or meandering (Leopold and Wolman, 1957). Straight channels are rare in nature and usually do not exist for distances longer than ten channel widths. Braided channels, which usually have steep gradients, are relatively unstable; lateral shifting of the channel and large sediment loads characterize braided channels.

Meandering channels generally are more predictable and are relatively stable. They are characterized by moderate slopes and are typical of stream channels found in the plains and high desert regions of Wyoming. The sinuosity of a meandering stream channel depends on a number of factors, including the slope of the valley, the magnitudes of the streamflow and sediment discharge in the channel, and the characteristics of the streambed material. The geometry of an idealized meander (fig. 15), for the purpose of this report, is described by its linear wavelength, meander length, meander amplitude, radius of curvature, and bankfull channel width.

The channel sinuosity is defined as the ratio of channel length to valley length; if the examined reach is short enough that the valley segment itself is straight, then channel sinuosity is the ratio of channel length to the straight-line distance, as defined by Friedkin (1945, p. 260-262). In figure 15, sinuosity (p) is the ratio of the stream length (Lm), in feet, to the linear wavelength (λ), in feet, of the meander:

$$p = \frac{Lm}{\lambda}. \qquad (8)$$

Equivalently, sinuosity of a reach can be defined as the ratio of valley slope (VAL-S), in foot per foot, to channel slope (CHAN-S), in foot per foot:

$$p = \frac{\text{VAL-S}}{\text{CHAN-S}}. \qquad (9)$$

Sinuosity substantially influences the geomorphic analysis of channel pattern. Schumm and Khan (1972) used flume experiments to show that sinuosity of a stream channel is a function of the slope of the valley; a steeper valley slope will cause a more sinuous meander pattern, up to a threshold value. Martinson (1984) used a similar analysis for the Powder River in Montana to identify meandering reaches that were stable or unstable for a given valley slope.

Channel sinuosity is a manifestation of the stream-channel slope on the existing valley slope (barring any geologic controls). The stream channel, by changing its sinuosity, adjusts its slope to attain a condition of quasi-equilibrium for the existing range of streamflows and sediment loads.

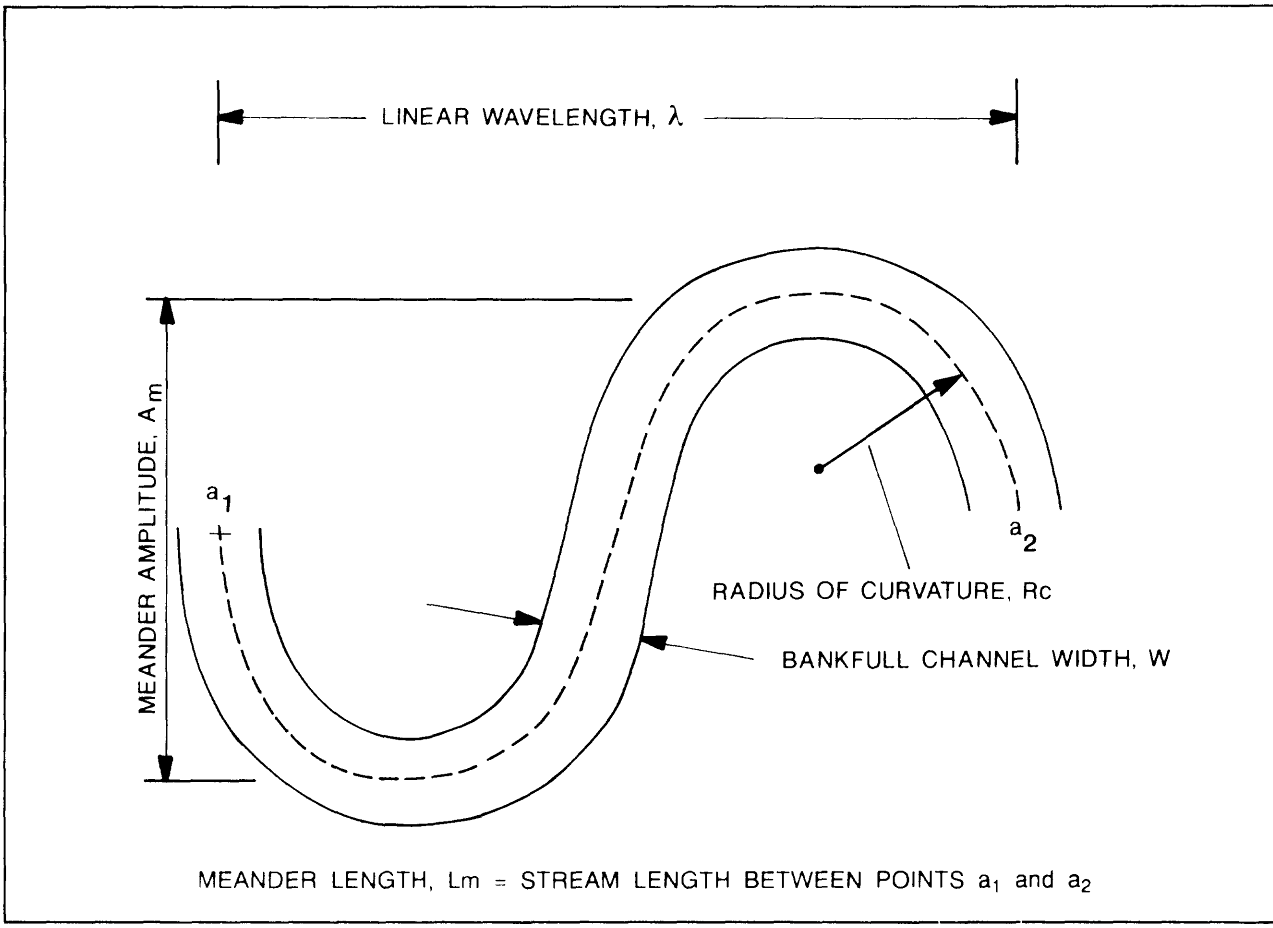


Figure 15.--An idealized stream reach with definitions of meander characteristics.

Selection of stable channel slopes for design is critical to the success of the reconstructed stream channels and drainage systems. Stable stream channels are identified as those having fairly permanent banks and beds over a period of years with a normal range of streamflows. Unstable stream channels change in reaction to each large streamflow, and the banks and beds are not well defined or permanent over a period of years.

Streamflow and Cross-Sectional Data

Streamflow data used for this part of the study were compiled by Lowham (1988). Empirical relations for width using the channel-geometry method are based on data for 68 streamflow-gaging stations operated by the U.S. Geological Survey in the plains and high desert regions of Wyoming (Lowham, 1988, p. 65-70). Bankfull discharges and cross-sectional properties used to develop hydraulic-geometry relations at gaged sites are based on data collected at 12 of the 68 stations; these data are listed in table 10. The smaller data set is the result of using only those stations having at least 5 years of continuous streamflow records.

Table 10.--Bankfull discharge and channel properties used to develop regional hydraulic-geometry relations

[Bankfull discharge approximated by 2-year annual peak flow (Lowham, 1988, p. 65-69); channel properties determined from analysis of current-meter discharge measurements available for each station]

Site No. (fig. 1)	U.S. Geological Survey streamflow-gaging station No.	Bankfull discharge (cubic feet per second)	Channel width (feet)	Mean channel depth (feet)	Cross-sectional area (square feet)
23	06239000	781	163	0.96	156
24	06256900	181	26	1.00	26.0
25	06257000	1,580	73	2.49	182
26	06267400	599	58	1.84	107
27	06268500	1,120	46	4.00	184
28	06286258	174	34	.48	16.3
29	06313000	2,760	146	2.95	431
5	06313180	277	17.5	3.40	59.5
30	06386500	3,160	127	5.00	635
31	06394000	1,000	44	6.41	282
32	06426500	797	74	3.91	289
33	09215000	265	57	1.75	100

Bankfull Discharge and Channel Cross Section

Geomorphic design of a stream channel for reconstruction is based on a design discharge, the bankfull discharge, which is approximated in this study by the 2-year annual peak flow. If sufficient measured streamflow data and peak flows are available for the reclamation site prior to disturbance, the 2-year annual peak flow might be identified from flow-frequency analysis. Likewise, if streamflow data and peak flows are available for nearby streams, a hydrologic analysis can be used to estimate the bankfull discharge for the site.

If site-specific streamflow data are not available (which commonly is the situation in the study area), then some other method for estimating the bankfull discharge is needed. A report by Lowham (1988) presents regionalized equations for estimating the 2-year annual peak flow. For the plains region (fig. 1), the equation (Lowham, 1988, p. 30) is

$$P_2 = 41.3\ A^{0.60\ A^{-0.05}} G_f, \tag{10}$$

where P_2 is bankfull discharge, in cubic feet per second;
A is drainage area, in square miles; and
G_f is a dimensionless geographic factor.

Equation 10 has a correlation coefficient (R) of 0.76 and an average standard error of estimate (SE) of 97 percent. For the high desert region (fig. 1), the equation (Lowham, 1988, p. 32) is

$$P_2 = 6.66\ A^{0.59\ A^{-0.03}} PR^{0.60} G_f, \tag{11}$$

where P_2 is bankfull discharge, in cubic feet per second;
A is drainage area, in square miles;
PR is average annual precipitation, in inches; and
G_f is a dimensionless geographic factor.

For equation 11, R = 0.80 and SE = 67 percent.

Detailed instruction for use of equations 10 and 11, including values of PR and G_f, and the applicable range of conditions for use of the equations, can be found in the report by Lowham (1988, p. 34, pl. 1).

Channel width from the channel-geometry method

For channel design, it is useful to define width as a function of discharge. Data from Lowham (1988, p. 65-70) for 68 streams in the plains and high desert regions of Wyoming were used in a regression analysis to develop the equation

$$W = 0.98\ P_2^{0.54}, \tag{12}$$

where W is bankfull channel width, in feet; and
P_2 is bankfull discharge, in cubic feet per second.

For equation 12, R = 0.87 and SE = 41 percent. An example illustrating the calculation of bankfull discharge and width for a given basin is presented later in this report.

Channel cross-sectional properties from hydraulic geometry

Discharge measurements are made routinely by field personnel at established streamflow-gaging stations throughout Wyoming; cross-sectional hydraulic properties, including width, area, and mean velocity of the streamflow, are determined. Measurements made over a range of discharges at a single cross section can be used to develop at-a-station hydraulic-geometry relations.

Data from current-meter discharge measurements were used to develop mathematical relations that describe the hydraulic characteristics for each of the 12 streamflow-gaging stations listed in table 10. The best relation was found to exist between cross-sectional area and discharge. Cross-sectional area was plotted as a function of discharge on logarithmic paper to produce a relation for each of the 12 sites. An example relation is shown in figure 16.

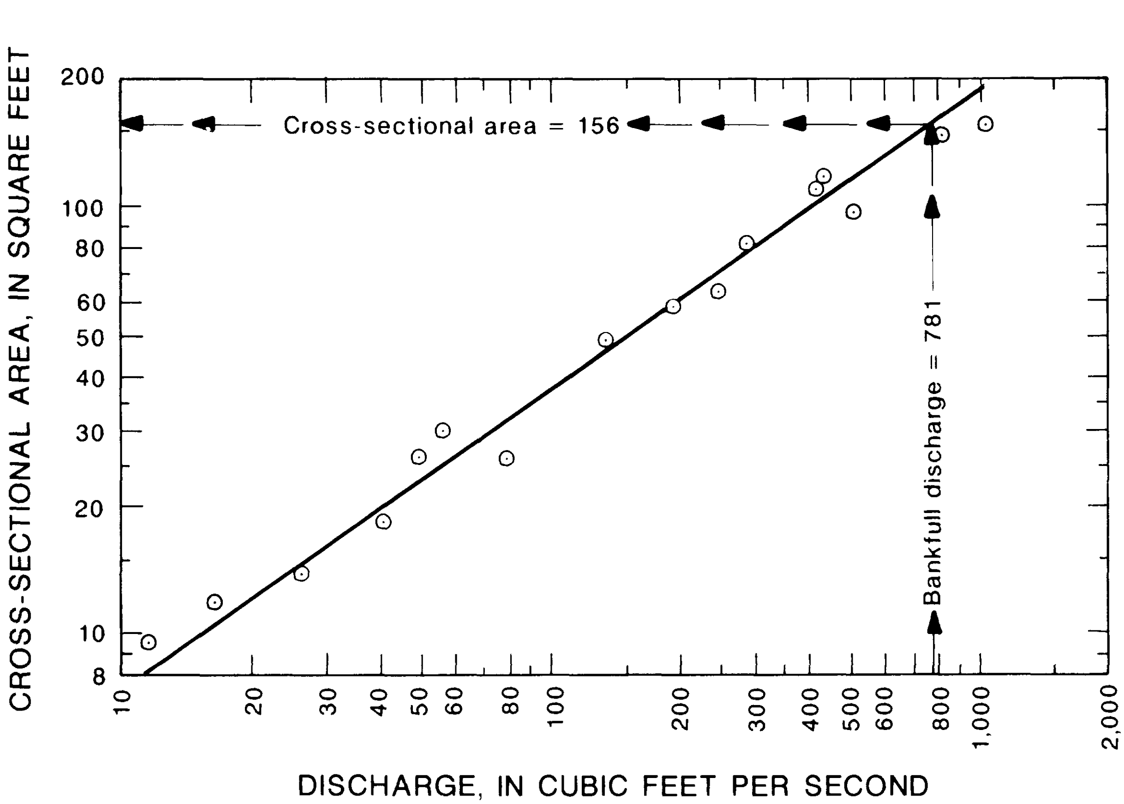


Figure 16.--Relation for channel cross-sectional area as a function of discharge at streamflow-gaging station 06239000, Muskrat Creek near Shoshoni.

From the straight-line relations, a cross-sectional area corresponding to bankfull discharge (2-year annual peak flow) at each site can be determined. For example, the estimated cross-sectional area for bankfull discharge (P_2 = 781 cubic feet per second) at Muskrat Creek near Shoshoni is 156 square feet (fig. 16). The relations can be used to develop average hydraulic characteristics for similar stream channels. Bankfull cross-sectional area as a function of bankfull discharge for the 12 sites (fig. 17) yields the following regional relation for similar streams in the plains and high desert regions:

$$A_c = 0.173\ P_2^{1.02}, \tag{13}$$

where A_c is bankfull channel cross-sectional area, in square feet; and
P_2 is bankfull discharge, in cubic feet per second.

For equation 13, R = 0.92 and SE = 46 percent.

Cross-sectional area is the product of width and mean depth; therefore, a mean channel depth (fig. 14) for design can be computed from:

$$D = \frac{A_c}{W}, \tag{14}$$

where D is mean channel depth, in feet;
A_c is bankfull channel cross-sectional area, in square feet; and
W is bankfull channel width, in feet.

The combined use of equations 12, 13, and 14 provides design values for channel width and mean depth for a given bankfull discharge.

Limitations

The empirical equations presented in this section were derived using sites having virtually natural streamflows. Application of the equations for reconstruction design depends on the existence of natural hydrologic conditions upstream from the reclamation site. Major dams, diversions, or other human factors will affect the natural hydrologic and hydraulic balance throughout the basin. For example, a given drainage area would have a smaller than normal bankfull discharge for design purposes if upstream diversions were present. In such cases, the equations for design discharge, width, and mean depth might not be valid.

Equations 10-14 are useful for estimating streamflow and channel characteristics only within the ranges of data used for their development. Equation 10 was based on data for 115 streamflow-gaging stations, equation 11 on data for 43 stations, and equation 12 on data for 68 stations. The ranges of data available for their development are described in detail by Lowham (1988, p. 26, 34). Equations 13 and 14 are based on data for 12 streamflow-gaging stations with ranges in data indicated in figure 17.

Analysis of Channel Pattern

Two geomorphic approaches for channel pattern are available for design of reconstructed channels. The first involves analysis of predisturbance maps and aerial photographs. Given similar basin and valley characteristics before and after disturbance, maps and aerial photographs showing the natural channel

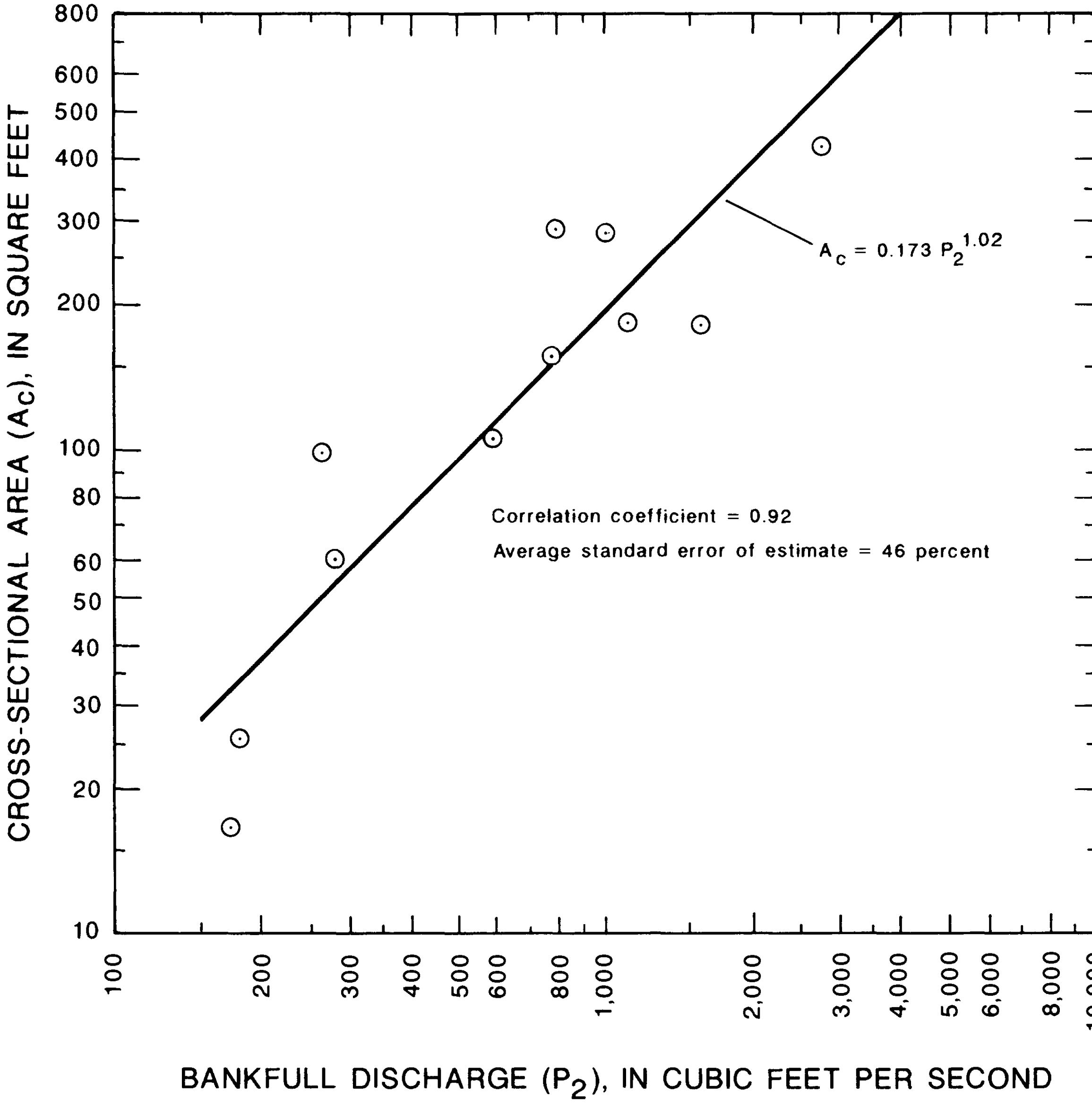


Figure 17.--Regional relation for channel cross-sectional area as a function of bankfull discharge.

can be used to estimate a channel pattern for reconstruction in terms of sinuosity, linear wavelength, meander length, meander amplitude, radius of curvature, and channel width. Strict replication of the predisturbance channel generally is not necessary (Harvey and others, 1985, p. 62). The second approach relies on empirical relations for meander characteristics as functions of basin characteristics.

Maps and aerial photographs

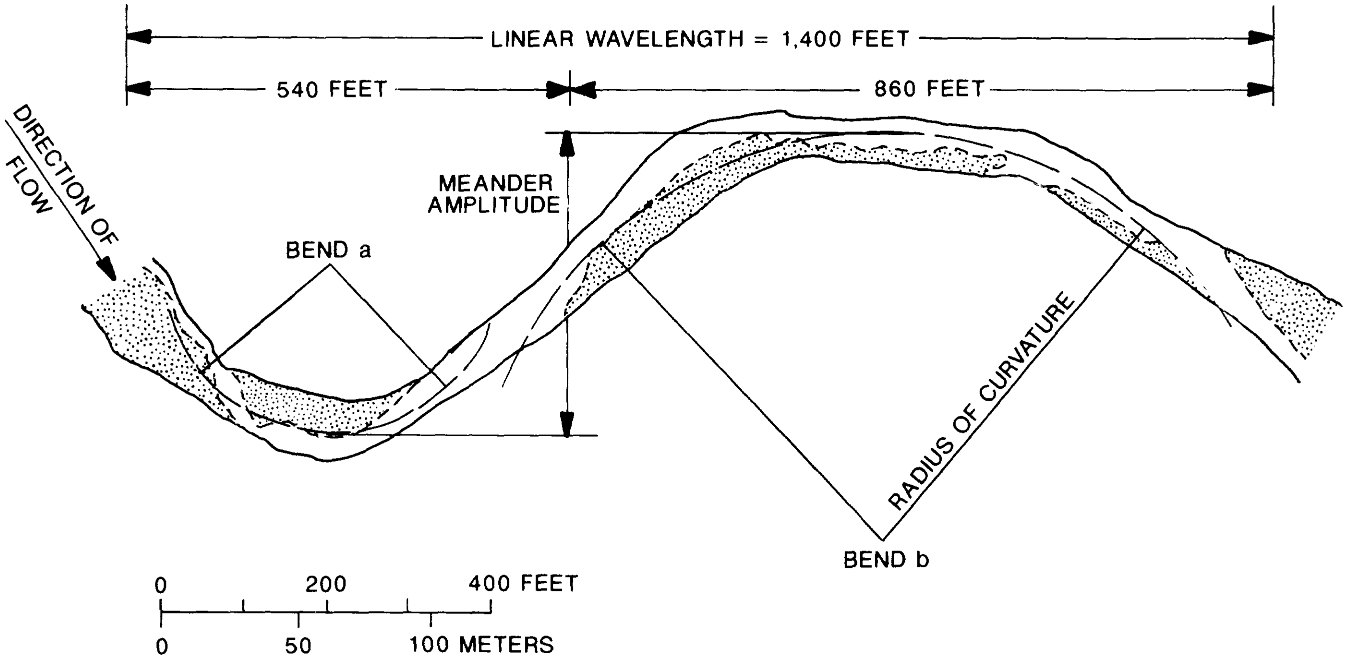
The stream or reach of interest is identified on each set of available predisturbance maps or aerial photographs. On the map or photograph sequences, pertinent pattern variables, such as sinuosity, meander length, amplitude, radius of curvature, and linear wavelength, are measured. Measurements of selected meander variables for an actual stream reach are shown in figure 18. Whether to measure the sinuosity for an entire reach (Brice, 1983), individual meanders (Rechard, 1980), or perhaps between successive topographic contours (Martinson, 1984) will depend on the available data and the interpretation of the investigator.

Once a design sinuosity is selected, corresponding values of meander characteristics can be chosen. Because numerous channel patterns can result in about the same sinuosity (fig. 19), a range of measured values for each characteristic might exist for stable meanders. Winkley (1983, p. 381) notes that a stream channel generally exhibits a range of radius of curvature of bends for which the stream will maintain its course.

Sinuosity can be determined either from values for streams of first- to fourth-order basins listed in tables 4-7, or from an average of measured values for the predisturbed stream. A channel pattern can be constructed by using the corresponding values of linear wavelength, meander length, amplitude, and radius of curvature. The meander pattern can vary somewhat, provided that values selected remain within the range of values observed for stable streams in the area. The use of more than one generation of maps or aerial photographs for several tens of years is helpful in identifying a stable channel pattern (the goal for design purposes), but analysis of a single generation of maps or photographs can yield an approximation of channel patterns when additional data are not available.

Empirical relations

If no predisturbance maps or aerial photographs are available, or if the disturbance has caused substantial alteration of geologic or geomorphic controls, empirical relations derived for similar stream channels (on the basis of region, climate, or geology) might be used for design of channel patterns. Only a few studies of this type have been done for ephemeral and intermittent stream channels in Wyoming. Widely used empirical relations for meander geometry, such as those proposed by Dury (1964) and Leopold and Wolman (1960), were derived for channels of larger perennial streams. The sinuous channels that characterize ephemeral and intermittent streams of the Wyoming plains and high desert regions are not typical of the channels of large perennial streams (Harvey and others, 1985, p. 62).



LINEAR WAVELENGTH OF FULL MEANDER = 1,400 FEET
= 540 FEET (BEND a) + 860 FEET (BEND b)

RADIUS OF CURVATURE FOR BEND a = 210 FEET
RADIUS OF CURVATURE FOR BEND b = 500 FEET

EXAMPLE: AN AVERAGE RADIUS OF CURVATURE, WEIGHTED BY THE LINEAR WAVELENGTH OF BENDS a AND b, IS DETERMINED BY RATIO OF DISTANCES:

$$\frac{[210\ (540) + 500\ (860)]}{1{,}400} = 390 \text{ FEET}$$

Figure 18.--Example of measurement of meander characteristics for a stream reach.

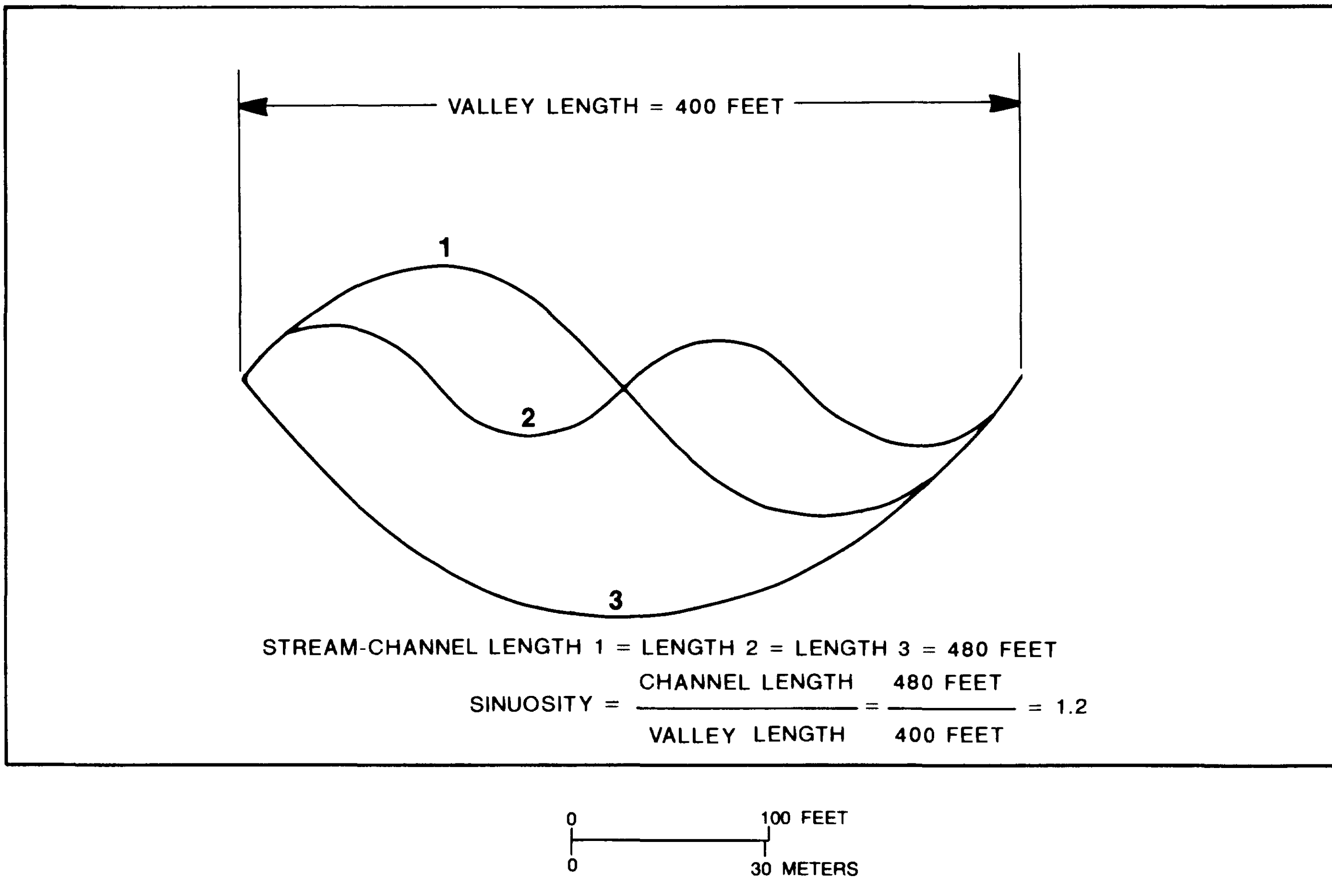


Figure 19.--Three different channel patterns having the same sinuosity.

Rechard (1980) examined the channel pattern characteristics of 11 ephemeral and intermittent stream channels in northeastern Wyoming. The study area is a part of the plains region identified by Lowham (1988). In his report, Rechard (1980, p. 231-239) plotted meander radius of curvature and meander length as functions of drainage area, and developed the relations

$$Rc = 65.5\ A^{0.35}, \text{ and} \tag{15}$$

$$Lm = 317\ A^{0.28}, \tag{16}$$

where Rc is radius of curvature, in feet;
Lm is meander length, in feet; and
A is drainage area, in square miles.

For equation 15, R = 0.85 and SE = 31 percent, and for equation 16, R = 0.84 and SE = 24 percent.

Equations 15 and 16 are based on drainage areas ranging in size from about 23 to 16,000 square miles. In another study, Divis and Tarquin (1981, p. 6.2) derived an equation for linear wavelength of meanders as a function of basin area, relief difference (equivalent to used relief in table 1), and channel slope for streams in the Powder River drainage basin. Their relation is

$$\lambda = 30.6\ A^{0.52} H^{0.09} Sc^{0.41}, \qquad (17)$$

where λ is linear wavelength, in feet;
A is drainage area, in square miles;
H is relief difference, in feet; and
Sc is channel slope, in foot per foot.

Equation 17 is based on the analysis of 37 drainage basins with drainage areas ranging from 0.7 to 1,500 square miles. This relation should be used only as an approximation, and only for stream channels with drainage basins of similar area in the Powder River drainage basin.

Limitations

The patterns of stream channels on maps or aerial photographs can differ considerably from one stream to another, or from reach to reach of the same stream. Reaches need to be analyzed and classified according to their channel pattern. For example, a stable meandering channel reach should not be analyzed along with an unstable braided channel reach. The statistical result would not represent the characteristics of either reach, and an undesirable design might be chosen. Classification schemes such as those developed by Culbertson and others (1967), Rundquist (1975), and Brice (1983) are useful in classifying stream reaches for geomorphic analysis.

Rechard (1980, p. 215) notes that analysis of predisturbance maps for the design of channel pattern is based on the assumption that geologic and geomorphic factors affecting channel pattern will be the same following reconstruction. If this assumption is not met, then some evaluation of the estimated effect of these factors needs to be included in the analysis. Divis and Tarquin (1981, p. 6.4) point out that, in the area being reconstructed, virtually all unconsolidated fill material will be fairly homogeneous; boulders will have been removed and bedrock outcrops that functioned as hydraulic controls will have been destroyed. Such changes could affect runoff, erosion and sedimentation, and channel morphology.

ILLUSTRATIVE EXAMPLES

Procedures for estimating physical characteristics of hypothetical drainage basins and stream channels that are to be reconstructed are given in the following examples:

Example A: Reconstruction of a Drainage Basin

Design estimates are needed for a headwater drainage basin of 1.9 square miles that has been disturbed by surface mining. The data and relation of drainage-basin order to drainage area in figure 8 indicate that, in the plains and high desert areas, a drainage-basin order of 2.8 is necessary to drain an area of 1.9 square miles. The number 2.8 rounds to the whole number 3, indicating that the main stream channel at the mouth of the drainage basin needs to be a third-order stream channel. The relations in figure 9 indicate that for a drainage area of 1.9 square miles 12 first-order, 3 second-order, and 1 third-order stream channels also are needed to complete the drainage network. The average slopes of first- to fourth-order stream channels and valleys are shown by the relation in figure 10, which illustrates that lower order stream channels and valleys have relatively steeper gradients than do higher order stream channels and valleys. The physical characteristics of the example drainage basin are summarized in table 11.

Example B: Estimating Design Discharge and Channel Width

An example basin being reconstructed is in the plains region (fig. 1). No streamflow-gaging stations have been operated on any streams in the area. The basin-characteristics method described by Lowham (1988) is selected to provide an estimate of bankfull discharge for the main stream. The stream has a drainage area (A) of 21.2 square miles and the geographic factor (G_f) is 1.4 (Lowham, 1988, pl. 1). From equation 10 (plains region), the bankfull discharge (P_2) to be used in the design is computed as

$$P_2 = 41.3\ A^{0.60}\ A^{-0.05} G_f .$$

Substituting A = 21.2 square miles and G_f = 1.4,

$$P_2 = 41.3\ (21.2)^{0.60}\ (21.2)^{-0.05} (1.4)$$

$$= 279 \text{ cubic feet per second.}$$

The design channel width for reconstruction is determined from equation 12:

$$W = 0.98\ P_2^{0.54} .$$

Substituting P_2 = 279 cubic feet per second,

$$W = 0.98\ (279)^{0.54}$$

$$= 20.5 \text{ feet.}$$

Example C: Estimating Channel Cross-Sectional Area and Mean Depth

For the same basin described in Example A, the design discharge (P_2) is 279 cubic feet per second. From equation 13 the channel cross-sectional area (A_c) is computed as

$$A_c = 0.173\ P_2^{1.02}$$

$$= 0.173\ (279)^{1.02}$$

$$= 54.0 \text{ square feet.}$$

Table 11.--Physical characteristics for hypothetical drainage basin

[BL, basin length, in miles; AREA, drainage area, in square miles; RELIEF, basin relief, in feet; UR, used relief, in feet; CHAN-L, channel length, in miles; and CHAN-S, channel slope, in foot per foot; see table 1 for complete description of the characteristics]

Drainage area = 1.9 square miles

Example design characteristics from figures 8 to 10 and tables 4 to 6

Basin order = 3 (fig. 8)

Drainage network = 12 first-order, 3 second-order, and 1 third-order stream channels (fig. 9)

First-order stream channels

Valley slope = 0.023 foot per foot (fig. 10)
Channel slope = 0.022 foot per foot (table 4 or fig. 10)
Sinuosity = 1.06 (table 4)

Second-order stream channels

Valley slope = 0.018 foot per foot (fig. 10)
Channel slope = 0.016 foot per foot (table 5 or fig. 10)
Sinuosity = 1.12 (table 5)

Third-order stream channels

Valley slope = 0.014 foot per foot (fig. 10)
Channel slope = 0.012 foot per foot (table 6 or fig. 10)
Sinuosity = 1.18 (table 6)

Example design characteristics from regression relations in table 9

Basin length = $BL = 1.81\ AREA^{0.49} = 1.81\ (1.9)^{0.49} = 2.5$ miles

Basin relief = $RELIEF = 224\ AREA^{0.27} = 224\ (1.9)^{0.27} = 266$ feet

Used relief = $UR = 1.57\ RELIEF^{0.79} = 1.57\ (266)^{0.79} = 129$ feet

Channel length of the dominant stream channel = $CHAN\text{-}L = 0.92\ BL^{1.15}$
$= 0.92\ (2.5)^{1.15} = 2.6$ miles

Channel slope of the dominant stream channel = CHAN-S
$= 0.00033\ BL^{-0.94} UR^{0.92}$
$= 0.00033\ (2.5)^{-0.94} (129)^{0.92}$
= 0.012 foot per foot

From equation 14 the mean channel depth (D) is computed as

$$D = \frac{A_c}{W}$$

$$= \frac{54.0}{20.5}$$

$$= 2.6 \text{ feet.}$$

On the basis of the calculations in Examples B and C, a design width of 20.5 feet and a design mean depth of 2.6 feet are chosen for channel reconstruction.

Example D: Analysis of Meander Characteristics

Consider a short reach of a hypothetical stream channel that was disrupted or destroyed and is being reclaimed. The stream was ephemeral, and there are no upstream human factors affecting streamflow. Examination of two sets of predisturbance aerial photographs, taken 15 years apart, reveals that 10 meanders did not change substantially and were fairly stable during that time.

The meander characteristics are sorted in order of increasing sinuosity as listed in table 12. The median indicates that a design sinuosity of about 1.28 can be used. After a review of the data, a range of sinuosity from 1.25 to 1.30 is chosen, with corresponding ranges of values for radius of curvature and linear wavelength:

Range for radius of curvature = 280 to 400 feet
Range for linear wavelength = 1,000 to 1,280 feet

The range of values for radius of curvature and meander length allows some flexibility in design, as long as the design sinuosity of 1.25 to 1.30 is maintained.

NEEDS FOR FUTURE STUDIES

Reclamation of large land areas in the arid and semiarid West has only been done for a few years; much needs to be learned concerning long-term processes affecting reclaimed drainage basins. Although there is extensive literature regarding fluvial processes in natural drainage basins, there is a paucity of literature reporting case histories of fluvial processes in reclaimed drainage basins. There is a need to establish a network of reclaimed drainage basins similar to the Vigil Network (Leopold, 1962) that exists for natural drainage basins. Reconstructed stream channels need to be included in such an evaluation program to document successes and failures and to expand the data base for future analysis. Desirable instrumentation for the network would include streamflow-gaging stations, monumented stream-channel cross sections, precipitation gages, and erosion grids for hillslopes.

Because of the nature of the semiarid climate and resulting infrequent runoff in the plains and high desert regions, it might take numerous years of data collection before sufficient data are available for analysis. In the meantime, additional studies are needed whereby onsite measurements are

Table 12.--Characteristics of stable meanders for example stream channel

Sinuosity	Average radius of curvature (feet)	Linear wavelength (feet)
1.10	240	680
1.15	500	1,840
1.20	340	1,440
1.25	320	1,280
1.25	400	1,240
1.30	280	1,000
1.35	280	800
1.35	290	1,200
1.45	180	1,040
1.50	600	1,760

Median = 1.28
Geometric mean = 1.29

accurately and systematically made and evaluated to define geomorphic variables, such as basin-surface and channel slopes, to assist in assessing optimum morphological characteristics of reconstructed fluvial systems.

The hydraulic significance of streambed and bank materials and the sediment loads transported by the stream generally is recognized (Richardson and others, 1987; Schumm, 1977; and Vanoni, 1975). Schumm (1960) used a sediment index to account for differing proportions of silts and clays found in the banks of streams. Similar data might assist future analyses of channel shape and pattern.

Harvey and others (1985) proposed a geomorphic approach to stable channel reconstruction that incorporates properties of channel cross sections, channel slope, and materials composing the streambed and banks. Their data included four ephemeral stream channels in the semiarid western United States. Three equations, based on regression analysis, were derived for the prediction of equilibrium channel width, average depth, and slope. Further application of this method in Wyoming could provide refined design procedures for channel reconstruction.

There is a need to refine the hydraulic-geometry relations for ephemeral and intermittent streams in the plains and high desert regions of Wyoming. Streamflow-gaging stations provide a basis for the development of relations between discharge and channel characteristics. Only 12 stations currently (1991) have long-term data available complete with current-meter measurements. Additional streamflow-gaging stations for ephemeral and intermittent streams, coupled with data from studies such as that by Apley (1976), could provide a refined set of regression relations for estimating the size and shape of reclaimed stream channels.

Few empirical relations that approximate the characteristics of stream-channel pattern are available for ephemeral and intermittent streams in Wyoming. Detailed studies of channel pattern are needed to develop relations applicable throughout the plains and high desert regions in Wyoming. The relations proposed by Rechard (1980) and by Divis and Tarquin (1981) are important because they were derived using data for stream channels in the plains region. Additional studies could expand the applicable range of these equations and provide refined empirical relations for the design of stream channel patterns.

CONCLUSIONS

The design and reconstruction of stable drainage basins for areas that have been altered by surface mining is critical to successful land use after reclamation. In addition to returning the mined area to a condition suitable for other uses, stable hillslopes and drainage networks are needed to avoid adverse effects in offsite streams from increases in erosion and sedimentation. Areas that have been reconstructed and reclaimed at active surface mines generally appear to be stable; however, the evaluation of long-term stability is difficult to assess because rilling and gullying that occur at these sites are repaired immediately.

For natural basins, drainage density increases toward the headwater areas as the drainage basin evolves. Mature drainage basins have well-developed drainage networks, which are efficient in rapidly transporting streamflow and sediment loads from the basin. However, field and laboratory studies of drainage development and sediment yield (Leopold and others, 1966, p. 239; Parker, 1977; Rankl, 1987, p. 15; and Zimpfer and others, 1982, p. 3) indicate that reconstruction of drainage basins to simulate an immature state of erosional development yields the most beneficial results in reclamation success. Successful reclamation is considered to have relatively high revegetation success and low annual sediment yields. Reclamation of drainage basins using this concept would involve reconstruction of only second- and higher order stream channels. First-order stream channels would be allowed to develop naturally.

Although additional first-order stream channels likely will form in the reconstructed drainage basins, the practice of reconstructing only higher order major stream channels is believed to have advantages of (1) producing flatter valley hillside slopes with resulting greater revegetation success, and (2) yielding smaller sediment discharges than if drainage networks were fully reconstructed to premining densities.

Successful reconstruction of disturbed stream channels requires the identification of channel characteristics that will be compatible with existing basin and hydrologic conditions. A geomorphic approach to analysis and design involves both channel cross-sectional properties and channel pattern. On the basis of measured sites in the plains and high desert regions of Wyoming, empirical predictive relations for bankfull channel width and mean depth as functions of bankfull discharge (approximated by the 2-year annual peak flow) are provided for use in stream-channel design for reconstruction. Testing these relations is needed at additional reclamation sites in the study region; monitoring of the reconstructed channels is needed to assess subsequent cross-section changes and channel erosion.

A geomorphic approach to stream-channel reconstruction also includes an analysis of channel pattern; reconstruction of a stable meander pattern will minimize erosion and related maintenance costs. Analysis of channel pattern changes through time using maps and aerial photographs often can identify stable meander characteristics for the study reach. If geologic features that controlled natural stream slopes and channel patterns were altered or destroyed during the disturbance, analysis based on natural channel conditions might not be valid. In such cases, empirical relations derived for stream channels in hydrologically and geologically similar regions could be used for channel-pattern design. Few relations for meander geometry (linear wave-length, meander length, and radius of curvature) are available for stream channels in the plains and high desert regions. More work is needed to expand and refine these relations.

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*U.S. GOVERNMENT PRINTING OFFICE:1993-774-207/60060