GEOMORPHIC PRINCIPLES, STABILITY AND RECLAMATION PLANNING[1]

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Abstract.--Geomorphology is the study of the earth's surface, its processes, the magnitude and frequency of those processes and the relationship between geomorphic processes and landform. Rate is a fundamental concept in geomorphology and rates vary greatly in time and space. Stability, in a geomorphic sense, is a state in which slight perturbations of the landscape are damped to return to the original state and do not lead to a progression toward a new equilibrium. Landscapes tend toward stability.

Hillslopes are the inclined part of the land surface and are the product of hillslope processes. For natural systems, in the short-term, hillslope form governs process, but in the long-term, process determines form. In reclamation situations, the form is determined by the backfill and grading plan, and therefore, so are the dominant processes. Two processes of primary importance for reclaimed lands are mass-movement and erosion. In general, reclamation activities that reduce erosion also reduce mass-movement, and therefore, this discussion focuses on controlling erosion. Gradient is the most important factor in hillslope erosion rates. Hillslope length is also significant, as are hillslope longitudinal and plan form. In general, with respect to control of erosion rate, reclaimed hillslopes should have low gradients, short lengths and a diversity of hillslope forms. In circumstances where this is not easily achieved, longitudinal and plan form, and height may be adjusted.

Stream channels receive flow and sediment from hillslopes and convey them to the basin outlet. Channel morphology is a function of the amount of water and sediment carried by the channel and the character of the bed and bank materials. Design criteria for channels can be determined by permissible velocity, allowable tractive stress, or geomorphic-hydraulic techniques. Reclaimed stream channels must be capable of transporting background levels of water and sediment discharge in order to provide a smooth transition between reclaimed and undisturbed channels.

Hillslopes and channels are integrated to form a channel network and drainage basin. Quantitative analysis of drainage basins shows that basin morphology and erosion rate is related to climate, lithology, and relief. Mining and reclamation may alter lithologic controls or relief suggesting that equilibrium drainage basin morphology will be altered by surface mining. Quantitative relationships between basin morphology and basin relief and lithologic characteristics can be used to design postmining equilibrium drainage basins based on the changes in relief and materials characteristics brought about by mining.

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INTRODUCTION

The science of geomorphology focuses upon the character of the earth's land surface. Most recent research examines the magnitude and frequency of geomorphic processes operating on the surface and the relation between process and resulting landform. The concept of "rate" lies at the heart of contemporary geomorphology, the rate at which a particular process or suite of processes performs geomorphic work, or the rate at which landforms change their morphology. Virtually all evidence confirms the dynamic nature off the earth's surface. The rates of both processes and landform modification vary considerably through time, and the extent of variability is partly a function of the time scale involved in a specific investigation.

The majority of geomorphologists agree that landscapes and landforms evolve toward a stable condition. Although the term "stability" may refer strictly to mass-stability to some earth scientists, it usually has a broader connotation for geomorphologists. Toy (1982) submits that stability is a state in which slight perturbations of the variables defining an environmental system do not lead to a progression toward a new steady or equilibrium state, but a return to the previous state. From the geomorphic perspective, reclamation is the re-creation of stable landscapes and landforms.

It is the aim of this treatise to present some geomorphic principles to guide the construction of stable surfaces. First, it must be recognized that nearly all surfaces can be divided into drainage basins, on the basis of morphology and geomorphic and hydrologic function. These drainage basins are, in turn, composed of hillslopes and channels.

Second, it must be recognized that drainage basins are open, process-response systems. All of the components are functionally related in complex interaction. Toy (1984) lists a number of established statistical relations among drainage basins, hillslopes, channels, and their environmental setting. These linkages reveal the reasons why instability in one part of a drainage basin may be conducted to other parts. Hence, a "domino effect" of reclamation failure can spread throughout an entire drainage basin. The forthcoming discussion considers geomorphic principles pertaining to hillslopes, channels, and drainage basins.

HILLSLOPES

Introduction

While a condition of stability is the general objective for hillslopes on reclaimed lands, the Permanent Program Performance Standards accompanying the Surface Mining Control and Reclamation Act of 1977 (PL 95-87) provide more specific goals. Disturbed areas shall be backfilled and graded to: (1) achieve the approximate original contour, except as specified, (2) eliminate all highwalls, spoils piles, and depressions, except as specified, (3) achieve a post-mining slope that does not exceed either the angle of repose or such lesser slope as is necessary to achieve a minimum long-term static safety factor of 1.3 and to prevent slides, (4) minimize erosion and water pollution both on and off the site, and (5) support the approved post-mining land use [Sec. 816.102(a), 1-5]. Further, topsoil materials shall be redistributed in a manner that: (1) achieves an approximately uniform, stable thickness consistent with he approved post-mining land use, contours, and surface-water drainage system, (2) prevents excess compaction of the materials, and (3) protects the material from wind and water erosion before and after seeding and planting [Sec. 816.22 (d), 1, a, i-iiii]. Finally, the permittee shall establish on regraded areas and on all other disturbed areas, except as specified, a vegetative cover that is in accordance with the approved permit and reclamation plan and that is : (1) diverse, effective, and permanent, and (2) capable of stabilizing the soil surface from erosion [Sec. 816.111 (a),1, 4].

In general terms, stable hillslopes should be devoid of mass-movement indicators and experience low to moderate erosion rates, similar to those of nearby undisturbed areas. Conversely, unstable hillslopes may exhibit evidence of mass-movement, such as slide scars, tension cracks, hummocky topography, and lobate landforms, or evidence of accelerated erosion rates, such as rilling and gully;. The Permanent Program Performance Standards specify that rills and gullies, which develop in areas that have been regraded and topsoiled and which disrupt the approved post-mining land use or the re-establishment of the vegetation cover, or cause or contribute to a violation of water-quality standards for receiving streams, shall be filled, regraded, or otherwise stabilized; topsoil shall be filled, regraded, or otherwise stabilized; topsoil shall be replaced; and the area shall be reseeded or replanted [Sec. 816.95 (b), 1, 2]. Before addressing the principles and problems related to the design of stable hillslopes, it is useful to lay a foundation through consideration of hillslope morphology and the relation between form and geomorphic processes.

Hillslope Form

A hillslope may be simply defined as an inclined land surface, extending from a crest or divide to a nearly horizontal valley-bottom or to a stream channel. A hillslope is the product of hillslope processes.

It is often convenient to examine the shape of a hillslope in terms of its plan form and its profile form. The plan refers to the shape along the horizontal dimension, or width, as depicted on a topographic map. If a series of contour lines trend parallel and linear, then the hillslope surface is rectilinear, and such a hillslope is referred to as a valley-side hillslope. If the series of contour lines is again essentially parallel but curvilinear and extending to higher elevations, in which case the hillslope is referred to as a spur-end hillslope (nose). Otherwise, the lines may be generally concave outward, with two adjacent valley-side hillslopes connecting and extending to lower elevations, in which case the hillslope is referred to as a valley-head hillslope (hollow).

The profile refers to the shape along the vertical dimension, or length, as depicted in the spacing of contour lines on the topographic map. If the series of contour lines is evenly spaced along the hillslope length, then the hillslope possesses a straight or uniform profile. If the series of contour lines is not evenly spaced, then there are again two possibilities. If the distance between lines increases toward the crest, at higher elevations, then the profile is convex. If the distance between lines increases toward the base, at lower elevations, then the profile is concave.

However, it is rather rare for the profile of a hillslope to assume a simple straight, convex, or concave profile. Usually, they consist of two or more elements or segments. Commonly, concavity. Such a convex-concave shape is believed by some to represent the "equilibrium" profile.

Although it is convenient to describe the form of hillslopes according to the plan or profile, in reality they are three-dimensional surfaces in most circumstances. Rule (1975) provides a valuable review of hillslope geometry, including the three-dimensional features.

Hillslope Form and Process

Abundant research has documented the relations among hillslope forms and the rates of geomorphic processes. The form influences process rates, but these rates also influence hillslope form. It has been suggested that over short time periods, process tends to govern form. These arguments become moot for reclaimed lands because, for the time periods of concern, form is a function of the grading operation and process rates are, in part, the result. Consequently, we are primarily interested in the opportunities to control process rates through the control of hillslope form.

The two hillslope processes of primary importance for reclamation lands are mass-movement and erosion. It is clear that the height and gradient of a hillslope strongly affect the propensity for mass-instability. Additionally, it is evident that the gradient, length, profile shape, and three-dimensional configuration of a hillslope influence surface erosion rates. In the interest of brevity, the forthcoming shall focus only upon the relations between hillslope form and erosion by water. Suffice it to note that the actions taken to control hillslope erosion by water are also likely to control mass-movement and wind erosion rates as well, in most situations.

It appears that every soil erosion equation includes a gradient variable in one way or another. The Environmental Protection Agency (1976) explains this relation:

"As slope steepness increases, there is a corresponding rise in the velocity of the surface runoff, which in turn results in greater erosion. A doubling of the velocity of water produced by increasing the degree and length of the slope enables water to move soil particles 64 times larger, allows it to carry 32 times more soil material, and makes the erosive power, in total, four times greater."

The review by Hadley, et al. (1985) shows that polynomial functions best represent the relation between gradient and soil loss, although the exponents apparently range from 0.70 to 2.0, depending on particular research conditions.

The relation between soil erosion and hillslope length usually assumes the development of Hortonian overland flow (Horton, 1945). Here, runoff accumulates in the downslope direction with concomitant increases in the depth and velocity of flow. Zingg (1940), Musgrave (1947), Kramer and Meyer (1969), and Laflen, et al. (1978) are among those supporting a significant relation between these two variables; and, again, the exponents for specific equations are variable.

Sometimes, the gradient and length variables are taken together in attempts to estimate soil loss, as with the Universal Soil Loss Equation (Wischmeier and Smith, 1978). The product of the length and steepness factors, LS, is the expected ratio of soil loss from a hillslope of given gradient and length to corresponding losses from a standardized plot. Israelsen, et al. (1980) show that this interacterance parameter is valid for fairly steep hillslopes (up to 84 percent).

Erosion rates are also influenced by the form of the hillslope profile. These relations are best summarized by Meyer, Foster, and Romkens (1975):

"Erosion at successive points downslope increases gradually for uniform slopes. Losses for convex slopes are lesser near the top but increase very rapidly toward the end of the slope. For concave slopes, losses are greater near the top of the slope but decrease along the lower portions to the extent that deposition may occur. For complex slopes, with their upper half convex and lower half concave, sediment load increases to a point approaching the toe of the slope, and thereafter deposition may occur."

Later, Meyer and Romkens (1976) elaborate upon these tendencies and shed light upon their cause:

"A convex slope is more erodible than a uniform slope, because it is steepest near the toe where runoff if the greatest. A uniform slope will yield more sediment than a concave one, because the concave slope is steepest where the flow is least and because some of the sediment eroded from the upper portions of the concave slope may deposit as it flattens near the toe.

A complex slope that is convex along its upper portion and concave along its lower portion will generally yield less sediment than a uniform slope. A flat section at the toe of a slope will also reduce sediment yield."

Within the profile itself, Hadley and Toy (1977) found that erosion from the straight mid-slope segment is nearly twice that of either the convex or concave segments. There may be either erosion or deposition in the basal concave segment, depending upon site factors, such as proximity to a channel.

Finally, Toy (1977) found that profile form varies with climate. Hillslopes in arid regions tend to be shorter, steeper, and have smaller radius of curvature in the convex element than those of humid areas. If these shapes represent steady-state conditions in these climatic regions, then perhaps the results of this study should be considered in hillslope grading.

The three-dimensional configuration of a hillslope partly controls of the direction of overland flow and so, logically, should influence erosion rates. For valley-head hillslopes (hollows), the flow lines tend to converge in the downslope direction so that, other things being equal, there are greater flows of water and sediment passing successive points downslope than on straight valley-side hillslopes. Conversely, on spur-end hillslopes (noses), the flow lines tend to diverge, so the flow of water and sediment tend to be less than on corresponding valley-side hillslopes (Carson and Kirby, 1972).

Of course, the above constitutes a somewhat cursory examination of the relations among hillslope forms and erosion rates. The exact nature of the relation is site-specific. Further, other site characteristics, such as soil and vegetation properties, significantly affect erosion rates. Nevertheless, the foregoing is commonly applicable to disturbed land and offers some guidance for the construction of hillslopes,.

General Principles of Hillslope Design

The principles presented here are derived from the relations among form attributes and erosion rates described above. First, spur-end hillslopes are the preferred three-dimensional design, wherever feasible. It is always better to disperse overland flow, rather than to concentrate it. Certainly, the entire reclamation landscape cannot be composed of spur-ends. However, we can infer that this form is less likely to geomorphic instability than its valley-head counterpart. Hence, supplemental erosion control practices may be less important on spur-ends than on valley-heads.

Second, the preferred profile design is concavity, with complex, uniform, and convex profiles comprising a ranking of progressively lesser desirability. It is better to have the hillslope steepest where the flow is least, rather than the converse, and provide the opportunity for sediment deposition before overland flow enters a receiving stream. Again, supplemental erosion control practices may be less important on concave profiles than on convex ones.

Design hillslopes are preferably gentle in gradient and short in length, although not necessarily flat. Horizontal surfaces tend to collect runoff. If sufficient in volume, this water will seek the low point on this surface and spill into adjacent lands as concentrated flow. Rills and gullies may develop at these points and grow headwardly,. dissecting the reclaimed area.

Usually, there is a trade-off to be considered in grading; as hillslope gradient is reduced, hillslope length increases. It can be shown, using a simple example of a uniform hillslope with a constant cross-sectional area, that the reduction in gradient more than compensates for the increase in length as far as erosion potential is concerned. In other words, as gradient decreases, the LS factor of the Universal Soil Loss Equation decreases, despite the increase in length. Thus, grading to reduce the gradient is clearly a preferred reclamation practice from a geomorphic perspective, whenever possible.

Problems in the Design of Stable Hillslopes

Both geomorphic and economic problems can be encountered in the design and construction of hillslopes on reclamation lands. The geomorphic problems become evident when the hillslope is geomorphically unstable. Accelerated erosion rates, manifested in the development of rills and gullies, indicate that the forces impinging on the surface are rather easily overcoming the resistances. This may be the consequence of revegetation failure and might be rectified by the replication of past revegetation practices. Alternatively, the problem may be more serious. The hillslope may be simple too steep or too long to permit tolerable erosion rates, and the higher rates preclude the establishment of an effective vegetation cover. In this case, retreatment without regrading is probably futile.

The economic problems precipitate from the fact that gradient reduction necessitates regrading and earth-moving is expensive, frequently the largest component of the total reclamation cost. Further, as hillslope length increases, the area over which topsoil must be distributed also increases and this again adds to the cost of reclamation. These is also a physical limit to the surface area that can be topsoiled to the depth required with the stockpiled material available.

Conclusion

Despite the regulation mandating the return of the surface to an "approximate original contour", the foregoing geomorphic principles remain valid. There are some geomorphic and hydrologic features of the reclamation surface that are not readily reproduced, such as lithologic and structural strength of the underlying material, infiltration capacity of the surface, and perhaps the erodibility of the replaced topsoil. Hence, there is little assurance that the hillslope forms that were geomorphically stable prior to disturbance will be necessarily stable following reclamation. The equilibrium or steady-state hillslope form is dependent in large part on site characteristics and some of these will likely be different, at least for a time. As a result, there will be some period during which hillslope form adjusts to the prevailing site characteristics. Sediment is usually the product of this adjustment and it can be stored on-site or transported to stream channels and through the drainage system.

By now, we realize that the relations between hillslope forms and hillslope processes are quite complex. Forms affect processes and eventually processes affect form. Hillslopes can take various forms and are visited by various processes. More detailed discussion of these relations with additional research documentation will soon be available (Toy and Hadley, to be published July 1987).

Lastly, it is worthwhile to reiterate that the drainage basin is an open process-response system, composed of hillslopes and channels engaged in complex interaction.

CHANNELS

Introduction

A channel is the naturally formed conduit for water and sediment discharging from the watershed. Where channel banks are composed of erodible materials, channel shape and slope will adjust to transport supplied water and sediment.

There is agreement among earth scientists that landforms, if undisturbed, will achieve a state of dynamic equilibrium with environmental conditions. For rivers, this is expressed by the engineer's concept of regime and by the gemorphologist's concept of grade. A channel in regime, or in a graded condition, does not progressively aggrade or degrade or change its dimensions, and is stable by the definition provided in the introduction to this paper. There may be annual variation about an average condition in response to floods, or prolonged periods of discharge, but during a period of years, the channel maintains its character and gradient. However, when there is a change of channel regime as a result of changed discharge, sediment load, or baselevel the channel will respond and adjust to such changes.

Channel Morphology and Pattern

The water and sediment discharge are the primary independent variables which influence channel morphology (Schumm, 1971a), and the dynamic equilibrium form of the channel system is the morphologic expression of those variables. Lane (1955b) presented a qualitative relationship between bed-material discharge (Q_s), water discharge (Q), sediment size (D_{50}), and gradient (S), as follows:

$$(Q_s)(D_{50}) = (Q)(S) \qquad (1)$$

Schumm (1971b) developed similar qualitative relationships which included, channel depth (d), meander wavelength (lambda), sinuosity (P), and channel width (b), as follows:

$$Q_s = (b)(\text{lambda})(s)/(d)(p) \qquad (2)$$

and

$$Q = (b)(d)(\text{lambda})/(S) \qquad (3)$$

Together, the three relations (Land, 1955b; and Schumm, 1971a, 1971b) allow qualitative prediction of changes in channel profile, or planform, as a result of change in an independent variable. For example, a decrease in the calibre (D_{50}^-) of the bed-material load at a given discharge will result in a decrease in slope (S^-). In natural stream this can be accomplished by channel incision. A decrease in bed-material discharge (Q_s^-) could result in a decrease of width (b^-), meander wavelength (lambda^-) and slope (S^-) and an increase of sinuosity (p^+) and depth (d^+).

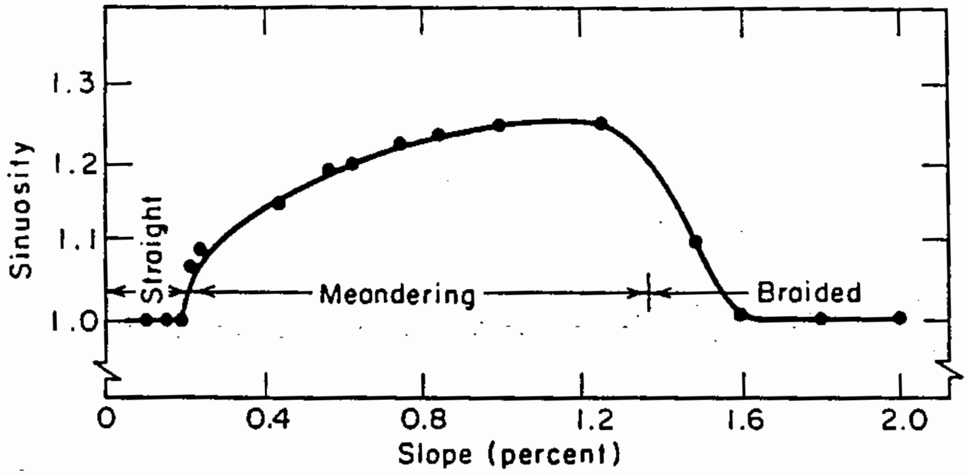

Figure 1.-- Relation between valley (flume) slope and sinuosity (channel length/valley length or valley slope/channel slope) during experiments at constant discharge. Sediment load, stream power, and velocity increase with slope and a similar relation can be developed with these variables (from Schumm and Khan, 1972).

Stream patterns are sensitive indicators of slope change (Schumm 1972, 1977; Schumm et al., 1972). Unfortunately, it is not possible to predict pattern and channel change precisely because different types of channel respond differently to slope change. Schumm and Khan (1972) demonstrated a complex relation between valley slope and sinuosity (Figure 1). Figure 2 shows a number of channel patterns which may result from combinations of the energy available to transport sediment and water, and the materials that are available for transport (Schumm, 1981).

Lane (1957) proposed a relation between alluvial channel slope, mean discharge, and channel form, as shown in Figure 3. From this relation at a mean discharge of 100 cfs, slopes greater than .0032 are characteristic of braided channels and those that are less than .00054 are characteristic of meandering channels. Intermediate slopes are indeterminate, and it has been suggested that the threshold relation for the channel patterns are not fully considered by the two variables (Carson, 1984). The diagram, however, does represent a reasonable approach to discrimination between channel patterns, that should be considered as part of any channel design procedure.

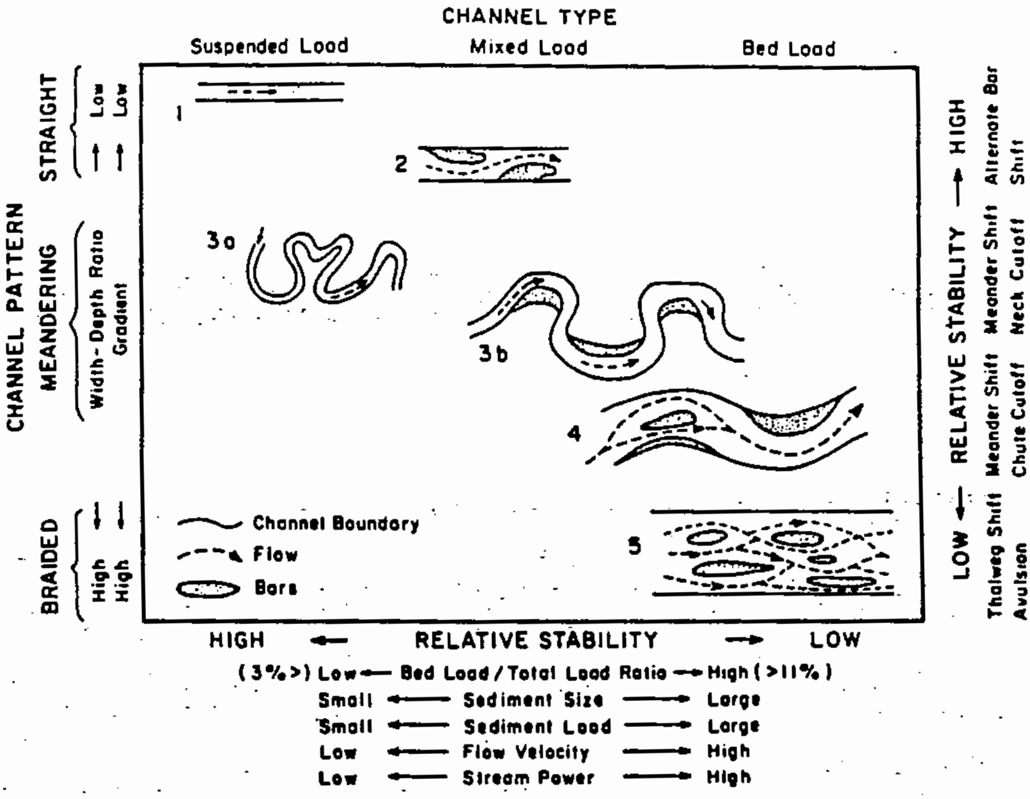

Figure 2.-- Channel classification based on pattern and type of sediment load with associated variables and relative stability indicated (from Schumm, 1981).

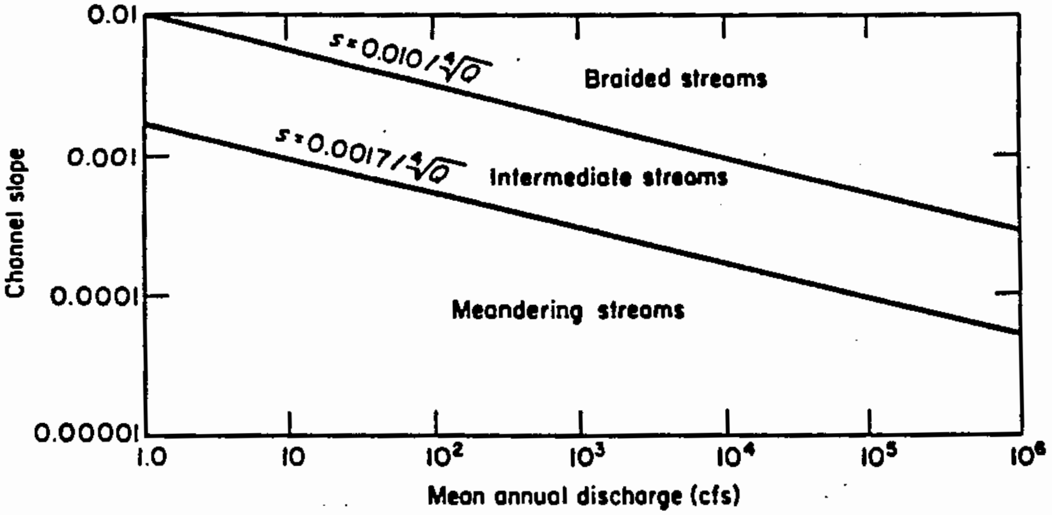

Figure 3.-- Relation between channel slope and mean discharge (after Lane, 1957).

Channel Design Procedures

Permissible Velocity

Probably the most commonly used design procedure for designing diversion and reclamation channels is based on permissible velocity criteria. for example, the Denver Urban Drainage and Flood Control District (1969) utilizes the following criteria:

> <u>Grass Lined Channels (Artificial)</u>. -- Grass lined channels may be considered to be the most desirable artificial channels. The channel storage, the lower velocities, and the sociological benefits obtainable create significant advantages over other types. The design must give full consideration to a esthetics, to sediment deposition, and to scour, as well as hydraulics.
>
> <u>Preliminary Design Criteria</u>.-- Preliminary design criteria are particularly useful in preliminary design and layout work. Any final design which has parameters which vary significantly from those below should be carefully reviewed for adequacy.
>
> <u>Design Velocity</u>.-- A maximum velocity for major design storm runoff needs to recognize the scour potential of the soil-vegetative cover complex. Average velocities need to be determined using backwater calculations which account for drops, expansions, contractions and other structural controls. Velocities need to be kept sufficiently low to prevent excessive erosion in the channel. The following velocities are recommended as maximums for major storm runoff flow:

MAXIMUM VELOCITY - (feet per second)

Grass Cover (^{1})	Erosion Resistant Soil	Easily Eroded Soil
a) None	4.0	2.5
b) Buffalo Grass, Blue Grass Smooth Brome, Blue Grama, Native Grass Mix	7.0	5.0
c) Lespedeza, Lovegrass, Kudzu, Alfalfa, Crabgrass	4.5	3.0

(^{1}) Assumes a well-maintained good stand of grass cover.

> <u>Design Depths</u>.-- The maximum design depths of flow should also recognize the scour potential of the soil-vegetative cover complex. Scouring power of water increases in proportion to the third to fifth power of depth and is also a function of the length of time flow is occurring. As preliminary criteria the design depth of flow for the major storm runoff flow should not exceed 5.0 feet in areas of the cross-section outside the trickle channel area.
>
> <u>Design Slopes</u>.-- Grass lined channels, to function well, normally have slopes of from 0.2 to 0.6 percent. where the natural topography is steeper than desirable, drops should be utilized.
>
> <u>Curvature</u>.-- The less sharp the curves, the better the channel functioning will be. In general, centerline curves should not have a radius of less than about twice the design flow top width, but not less than 100 feet.

The background data to support these or similar criteria are generally based on the experience of the agency promulagating their use; however, publications by the U.S. Department of Agriculture are commonly cited. Lane (1955a) provided a thorough review of permissible velocity literature. He listed three sources of data (Etcheverry, 1915;

Fortier and Scobey, 1926; USSR, 1936) and explained the limitations of each data set. The Russian reference provided the most complete information in 1955, and it provided permissible velocities for various bank materials with varying amount of suspended load, for a range of canal depths. The U.S. Department of Agriculture (1977) publication is now the most complete reference, on permissible velocity.

Allowable Tractive Stress

E.W. Lane is generally recognized for developing the tractive stress procedure for the design of stable channels during his work for the U.S. Bureau of Reclamation in the early 1950's. Lane (1952), and Land and Carlson (1953) describe the theoretical development, the empirical studies on coarse, granular, material in the San Luis Valley, and the development of tentatively recommended applications of the tractive stress approach to fine, noncohesive material. The work was summarized in Lane (1955a).

Lane (1952) reviewed stable channel design practice, noting primarily, that velocity was not a complete descriptor of the processes affecting channel stability. His work on tractive stress centered on two major areas: the distribution of tractive stress at the channel boundary, and the maximum allowable (limiting) tractive stress for various size boundary materials.

Determination of the limiting tractive stress for various materials was divided into two groups, coarse material ($D_{75} > 5mm$), and fine material ($D_{50} < 5mm$). In 1950 and 1952, Lane collected flow, slope, velocity, and sediment size data for eighteen test sections on irrigation canals in the San Luis Valley with D_{75} greater than 5mm. Based on these data, Lane then determined relations for hydraulic roughness and tractive stress as a function of material size ($D_{75} > 5mm$). Lane's primary interest was to provide guidelines for construction of new irrigation canals. He was not attempting a field duplication of Shield's (1936) efforts, which investigated the beginning of motion of particles; therefore, it is not surprising that Lane defined his relations for the hydraulic roughness (Manning's n) and limiting tractive stress as functions of the material through which the canal was originally constructed, i.e., the bank material.

The relations in the Soil Conservation Service Design Manual, TR-25 (U.S.D.A, 1977), are the same as those presented in Lane (1952). for the D_{75} of the material sized between 0.25 - 5 inches, the hydraulic roughness (n) and limiting tractive stress relations are:

$$n = D_{75}^{1/6}/39 = 0.0256\ (D_{75(bank)})^{0.17} \qquad (4)$$

and

$$tau = 0.4(D_{75(bank)}) \qquad (5)$$

These relations are applicable to construction of new irrigation canals originally, and not to the analysis of existing channels were bed material size data were available.

Watson et al. (1986) conducted a statistical analysis of the original bed and bank material data of Lane and Carlson (1953) and the results are:

$$tau = 0.2088\ (D_{50(bed)})^{1.26} \qquad (r^2 = 0.95) \qquad (6)$$

The statistical analysis showed that Lane's original expressions were closely represented by statistically significant least-squares regression relations.

Lane (1952) did not have field data for canals in fine materials and he utilized the permissible velocity data of Etcheverry (1915), Fortier and Scobey (1926), and the USSR (1936) to synthesize data for tractive stresses. He assumed a channel cross-section of 1.5:1 side slopes, a bottom width of 10 feet, a depth of 3 feet, and a Manning's roughness of n = 0.02. Manning's relationship was then used to compute slope and the simple product, (tau)(d)(s) was used compute to tractive stress. The results are tabulated with the original title, as follows (Table 1):

Table 1. Tentatively recommended Limiting Values of Tractive Force for Canals in Fine, Noncohesive Material.

	Limiting Tractive Stress (lb/sq. ft.)		
Median Size (mm)	Clear Water (<1000 ppm)	Low Content (<2000 ppm)	High Content (20,000 ppm)
.1	.025	.050	.075
.2	.026	.052	.078
.5	.030	.055	.083
1.0	.040	.060	.090
2.0	.060	.080	.110
5.0	.140	.165	.185

Following Lane, Simons (1957), who was investigating regime methods, complied a data set from field measurements of fine-grained irrigation canals. Figure 4 (Watson et al. 1986), shows the relations between Simons' (1957) data, Lane's (1952) recommendations, and Lane and Carlson's (1953) San Luis Valley data. All data are plotted as a function of D_{50} of the bed material. All of Simon's data represented total sediment load less than 500 ppm, and the average value for his data is 0.023 ± 0.0004 lbs/ft^2. The channel slopes measured by Simons were all less than .0004. Figure 4 shows that Lane's tentatively recommended values are conservative. The curve that represents Lane's tentatively recommended clear water [TSS<1000ppm] values forms a lower envelope for Simons' (1957) field data. Further, with the available data, there is no justification for the sharply upward sweeping trend of Lane's recommendation for channel perimeter sediment sizes between 1 mm and 5 mm.

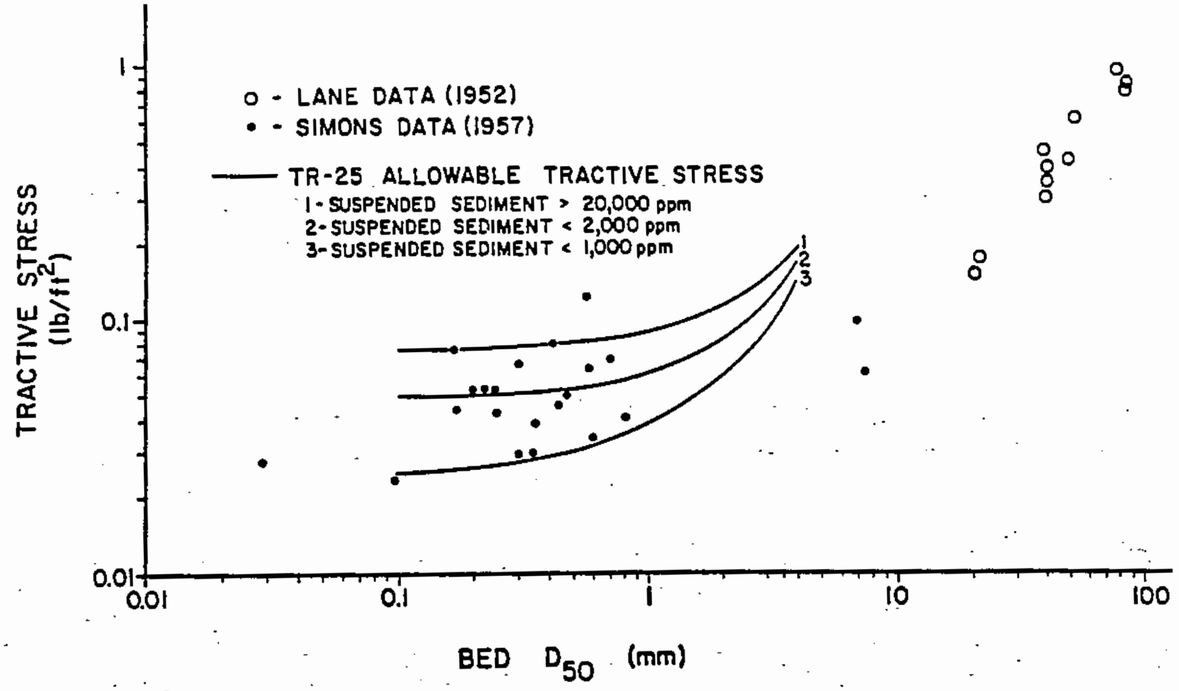

Figure 4.-- Comparison of tractive stress for bed material size D_{50}.

Lane (1953) compared several of the recommended relationships for design of stable channels and banks (Figure 5). Similarly, Chien (1954) compared several of the critical tractive force relations which had been used to predict the initiation of bed particle motion; this comparison is reproduced as Figure 6. Obviously, for a given sediment size, these two diagrams illustrate a wide range of tractive stress values and agreement on a single relation is not very good.

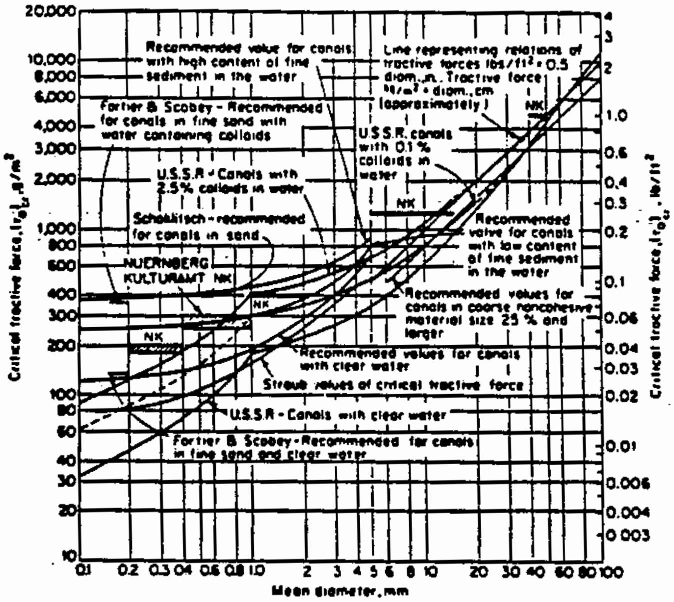

Figure 5.-- Critical shear stress as a function of grain diameter (after Lane, 1953).

One reason for the wide range of variation is that different researchers used different definitions of the critical condition. Lane (1953) was concerned with defining the tractive stress in actual canals that he observed in the field to be stable. Shields (1936) interpreted the critical conditions as zero sediment transport. As technology has become more sophisticated, the definition of the critical condition has changed as the result of observation with high-speed photography (Grass, 1970) and observations of the effects of micro-turbulence (Vanoni, 1964).

Both Lane's estimates and Simons data (Figure 4) confirm that for granular materials less than 5 mm in size, a tractive stress of 0.1 lbs/ft^2 will initiate motion. At a slope of 0.0001, and with a flow depth of 2 feet, the tractive stress is 0.124 lbs/ft^2; however, the velocity as computed by Manning's relation is 1.4 ft/sec., well below permissible velocity allowable limits. Therefore, sediment transport capacity is available in steep, grass-lined, cohesive-material channels which approach maximum permissible velocity limits. Stability of such a channel is due to the cohesive nature of the bed and bank materials, the resistance of the vegetative lining, and perhaps because the capacity to transport sediment is balanced by the sediment supplied from sources other than channel erosion.

Permissible velocity or tractive stress procedures when applied to relatively steep reclaimed western channels generally require the use of slopes beyond the range of slopes initially used in development of the procedures; however, the permissible velocity method has been widely applied and a body of experience and information is being developed.

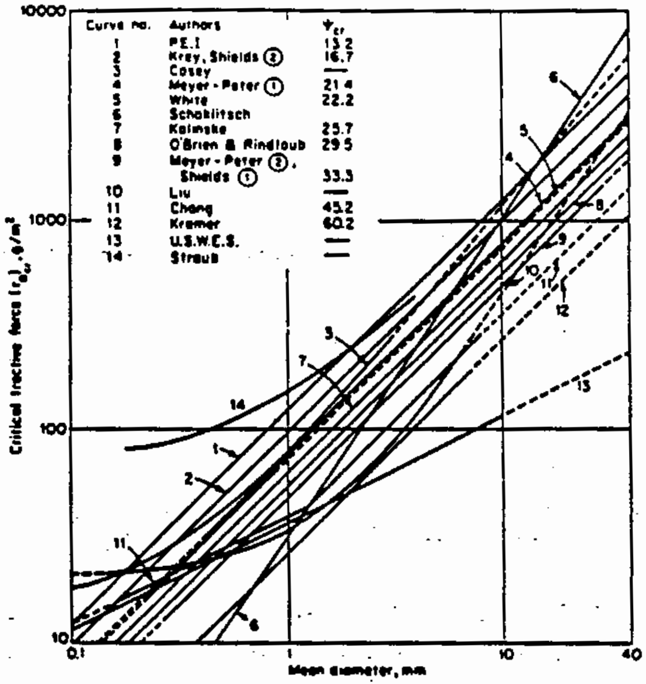

Figure 6.-- Critical shear stress as a function of grain diameter; a comparison (after Chien, 1954).

Permissible velocity criteria do not uniquely determine the cross-section shape, and it has already been established that channel morphology and discharge are related. As a practical matter, the use of a very wide and shallow channel to reduce velocity is not a good solution because minor variations in bed elevation or any concentration of flow will cause scour of a narrower, deeper channel within the limits of the wider channel.

Geomorphic-Hydraulic Approach

The results of studies of incised channel evolution in south-eastern (Schumm et al., 1984), mid-western (Harvey, 1984) have enabled a procedure to predict equilibrium channel morphology to be developed. This procedure integrates channel morphology, discharge and the sedimentologic characteristics of the channel-forming materials with may result from mining activities, can be accommodated in the procedure. This procedure is intended to be utilized,with existing procedures, as as another tool for use in reclamation.

Schumm, et al., (1984) concluded that, in spite of the apparent diversity of incised channel morphology which is related to climatic conditions and to the character of the materials into which the channel is incised, all incised channels follow the same evolutionary trend with eventual development of relatively stable conditions. Schumm et al., (1984) developed a model of channel evolution, that utilized a location-for-time substitution technique (Figure 7) to describe the changing morphological characteristics of an evolving channel. The five reach types (I to V) in the model represent conditions ranging from disequilibrium (I) to a new state of dynamic equilibrium (V).

In terms of the Schumm, et al., (1984) model, Type I and II reaches are characterized by incision which results in slope reduction. Type III reaches widen rapidly as a result of the exceedence of a bank height stability threshold, and some aggradation takes place in the bed of the channel. Type IV and V reaches are characterized by equilibrium channel slopes, and reduced channel depth, as a result of several feet of aggradation. Reduction of channel depth reduces bank heights to below threshold values. The channel evolution sequence has been recognized in a variety of environments, and field identification of the type IV and V reaches can provide a basis for engineering design, since they represent natural dynamic equilibrium reaches. In other words, these types of reaches represent dynamic-equilibrium morphologies in which there have been interdependent adjustments of channel slope and cross-section area that maintain the continuity of water and sediment transport (Leopold et al., 1964). Watson and Harvey (1984) and Harvey et al. (1985) used this approach to determine some equilibrium criteria for four channels in the western U.S., and they suggested that these criteria could be utilized in the design of new channels.

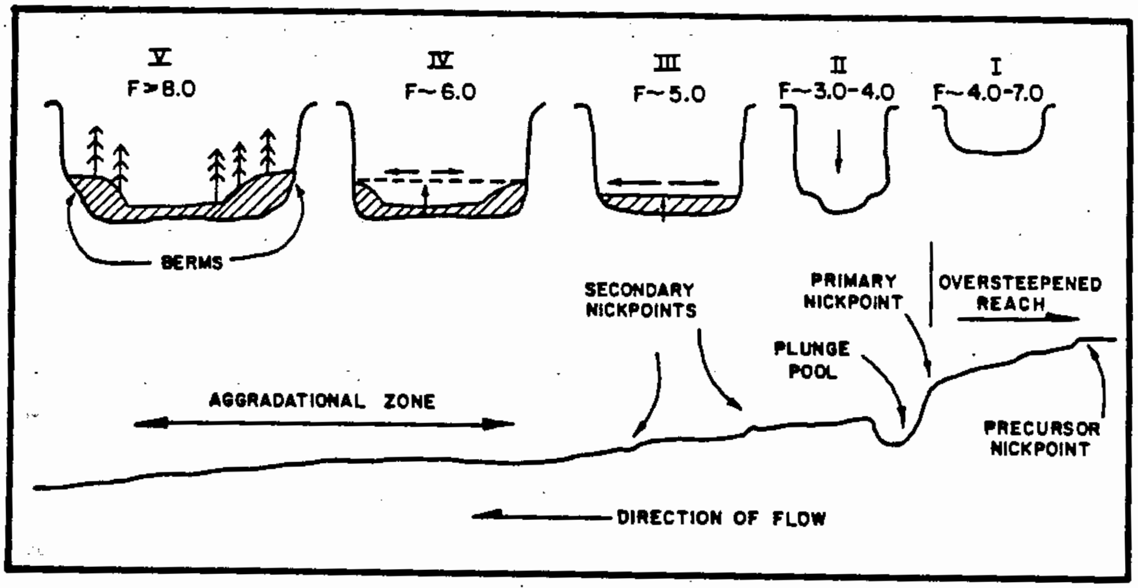

Figure 7.-- Schematic representation of the channel evolution model. Arrows indicate the relative importance and direction of the dominant changes.

Data from four western incised channels were obtained from U.S. Geological Survey Professional Paper 352-C (Schumm, 1961). The four channels are Sage Creek, South Dakota; Sand Creek, Nebraska; Bayou Gulch, Colorado; and Arroyo Calabasas, New Mexico. The flow in these channels is ephemeral and they are located in semiarid areas.

Data for each of the channels included a longitudinal profile, cross-sections, drainage area above each section, D_{50} of the bed material, a weighted percentage of silt-clay in the bed and banks (M), and a classification of the stability of each cross-section. Hydrologic records were not available for these four channels. Therefore, the product of the drainage area and the channel slope at each cross section was used as a surrogate for stream power. Since drainage area is a surrogate for discharge, and channel slope is a surrogate for energy slope, then, the product is a measure of stream power since the discharge-slope product has been defined as stream power (Henderson, 1961). Schumm et al (1984) and Harvey et al. (1986) made this substitution, referring to the drainage area-channel slope producet as the Area Gradient Index (AGI). AGI can be used in the preliminary phase of planning if design hydraulic and hydrologic data are unavailable. final design should incorporate both hydraulic and hydrological data.

Henderson (1961) and Wolman and Brush (1961) demonstrated that the wetted perimeter of a channel increases with stream power (QS). Henderson included the median grain size (D_{50}) of the bed material to improve the relation between wetted perimeter and stream power:

$$\text{Wetted Perimeter} = (QS)^b \, (D_{50})^c \qquad (7)$$

Richards (1982) states that channel top width is approximately proportional to wetted perimeter for wide channels.

Schumm (1960) recognized that the median grain size (D_{50}), as a single descriptive parameter, of the channel sediments failed to account for the sorting of the material. In addition, he suggested that sediment less than 0.074 mm in size greatly influenced the physical behavior of the channel. The result of that study showed that the width/depth ration (F), which is defined as the bankfull top width divided by the bankfull maximum depth, in stable channels was a function of the weighted mean percentage of silt-clay (M) in the perimeter of the channel. The F-M relation for the four channels is:

$$F = 102.5\ (M^{-0.79}) \qquad (r=.91) \qquad (8)$$

Table 2 lists the pertinent data for sixteen cross-sections which were determined, on the basis of the geomorphic model of channel evolution, to be in a state of dynamic-equilibrium.

Table 2 -- Morphologic, energy and grain-size data for Sage Creeks, Arroyo Calabasas and Bayou Gulch.

Site	Width (m)	Depth (m)	AGI (km^2)	Slope	M (%)	D_{50} (mm)
Sage Creek	4.88	2.13	.024	0.0055	73.0	.06
	6.10	2.13	.040	0.0045	79.0	.06
	9.46	1.52	.111	0.0045	54.0	.12
Sand Creek	10.98	0.91	.150	0.0035	23.0	.30
	22.88	2.13	.070	0.0015	23.0	.72
	19.83	2.13	.172	0.0030	22.0	.73
	10.98	1.22	.058	0.0010	20.0	.35
Arroyo Calabasas	24.10	0.91	.129	0.0030	4.1	.84
	20.44	1.37	.466	0.0040	4.1	1.00
	25.62	1.52	.219	0.0000	9.0	.85
	19.22	0.30	.231	0.0000	2.4	.90
	28.06	1.22	.564	0.0090	4.8	.50
	30.50	1.22	.735	0.0110	5.8	.75
Bayou Gulch	63.14	0.76	.438	0.0130	2.0	.74
	37.21	0.61	.441	0.0090	5.9	.50
	39.70	0.91	.509	0.0100	4.4	.58

Based on the work of Wolman and Brush (1961), Henderson (1961) and Schumm (1960), Watson and Harvey (1984) developed a relation between channel top width (TW), Area Gradient Index (AGI), median grain size (D_{50}) and the percent silt-clay in the perimeter sediments (M), which has the general form:

$$TW = a\ (AGI)^{b}\ (D_{50})^{c}\ (M)^{-d} \qquad (9)$$

The top width (TW) relation that was derived from the data presented in Table 2 is as follows:

$$TW = 53.2\ (AGI)^{0.26}\ (D_{50})^{0.24}/(M)^{0.16} \qquad (10)$$

The correlation coefficient (r) for the regression is 0.91. Each of the independent variables was also highly correlated with top width (AGI, r=0.82; D_{50}, r=0.83; M, r=0.85).

Utilizing the same data set a least-squares regression relation was derived for the equilibrium depth (d) of the channel:

$$d = 0.51\ (D_{50})^{0.27}\ M^{0.58}\ (AGI)^{0.12} \qquad (11)$$

The correlation coefficient (r) for the relation is 0.78.

In order to eliminate the effects of autocorrelation AGI, which is defined as the drainage area-slope product, was not used as an independent variable in the prediction of a equilibrium channel slope (S):

$$S = 0.03\ (D_{50})^{-0.60}\ (M)^{-0.82} \qquad (12)$$

The correlation coefficient (r) for the regression relation is 0.77.

The multiple regression relations that were developed from the dynamic-equilibrium reaches of the four ephemeral channels of the western U.S. should be of assistance in the design of channels, because they are based on natural system behavior which incorporates transport of bedload-size sediment. The approach is predicated on two assumptions. First, the dynamic-equilibrium reaches of an incised channel can be recognized (Schumm et al., 1984; Watson and Harvey, 1984), and second that the dimensions of a channel are a function of stream power and the nature of the perimeter sediments (Wolman and Brush, 1961; Henderson, 1961; Schumm, 1961).

The regression relationships (Equations 10, 11, 12) are, by definition, empirical, and, therefore, they should only be used in situations that fall within the original data set (Table 2). Application of this procedure to a specific site should include on-site measurement of stable channels in the same or similar watersheds. Comparison of the results of this procedure, with other procedures, will provide the experienced designer a broader base on which to make decisions, and will provide valuable information about background conditions.

Conclusions

This review of (1) the variables that determine channel morphology and planform, (2) the two most commonly used channel design procedures (Permissible Velocity and tractive Stress), and (3) a geomorphic-hydraulic approach to channel design enable the following conclusions to be drawn:

1. Natural stream channels, if undisturbed, are in a state of dynamic equilibrium. This is not a static state, but it encompasses a range of responses to minor changes in the controlling variable,s such that adjustments occur without any long term progressive change.

2. Channels can adjust their cross-section, slope, and planform in response to changes in sediment or water discharge.

3. Commonly accepted permissible velocity criteria can result in the design of channels with significant sediment transport capacity when the method is applied to relatively steep channels; however, the procedure is useful.

4. A physically based geomorphic-hydraulic design procedure can be used to design channels that are capable of transporting the sediment that is supplied to them. The empirical relations, on which this procedures is based, can be generated for stable channels, that are located nearby.

5. Reclaimed channels must be capable of transporting both the water and sediment that is delivered to them. background levels of both sediment and water discharge should be the design criteria, because the use of these values will permit a smooth transition between the reclaimed channel and unmined channel segments.

DRAINAGE BASINS

Introduction

The integration of hillslopes and channels into a drainage network forms the drainage basin, often referred to as the basic hydrologic, geomorphic or landscape unit (Chorley et al., 1984). As stated at the outset of this paper the drainage basin is an open system in which input of precipitation produces an output of water and sediment. The morphology of a drainage basin is the result of erosive forces due to flowing water and resistance forces of the geologic materials underlying the basin. Fluvial processes shape the majority of the earth's surface, especially in semiarid regions.

The performance standards that apply to reclamation of hillslopes and channels also apply to the drainage basin. Specifically, a mine operator shall prevent additional contributions of suspended solids to receiving streams; minimize erosion and channel enlargement; regrade to approximate original contour blend reclaimed drainage into surrounding terrain and repair rills and gullies that may form subsequent to regrading, topsoiling and seeding. Hillslopes and channels are capable of producing excessive amounts of sediment, and therefore, sediment control techniques must be considered for all components of the basin. Solutions to regulatory compliance are best approached on a drainage basin scale.

Drainage Basin Form

Quantitative analysis of drainage basin form was introduced by R.E. Horton (1945) and extended by A.N. Strahler (summarized 1964). The drainage basin has been considered a "viable process-response unit" (Chorley et al., 1984; Gregory and Walling, 1973) since the beginning of the last century, however, initial analyses were qualitative in nature (Playfair, 1802; Gilbert, 1877; Davis, 1899; Glock, 1931). Quantitative drainage basin analysis provides a measure of basin form which can be related to process thus enabling a greater understanding of the response of a basin to changes. Measures of basin morphology can be divided into four categories (Chorley et al., 1984): 1) linear, 2) areal and planform, 3) relief, and 4) gradient.

Linear measurement of drainage basin features includes the length of stream channels, ordering of streams channels, length of overland flow, basin length, and basin perimeter. Areal properties of drainage basin form include basin area, drainage density, stream frequency, basin elongation, and basin circularity. Relief can be measured by relief ratio and hypsometric (or area-elevation) analysis, revealing the distribution of mass within a watershed. Gradient can be measured on hillslopes, valley side-slopes, and in stream channels.

All the form elements of a drainage basin are closely interrelated in fluvially eroded topography. Chorley, et al (1984, p. 257-258) provide the following discussion of the relations between hillslopes, channels, and relief.

> "First of all, what is needed is relief, a surface elevated sufficiently above baselevel, so that stream incision can take place, and slope forms can develop adjacent to the incising channel. In an area of uniform lithology, climate and stage of development characteristic slope angles will form. Strahler's (1950) California study showed clearly that the hillslopes cannot be considered separately from the drainage basin as a whole, for what is happening on the interfluve areas between the streams will have a dominant influence on the character of the streams themselves and on the hydrology of the drainage basin. Therefore, when Strahler found that "maximum slope angles tend to be normally distributed with low dispersion about a mean value determined by drainage density, relief and slope profile curvature", he was concluding that the character of the slopes themselves is determined largely by the relief and slope profile curvature", he determined largely by the relief available. The greater the relief, the steeper the slopes. In addition, drainage density, which reflects the spacing of streams, is also going to affect the angle of inclination and length of slopes. The more closely the streams are spaced, the steeper will be the slopes (Figure 8). Strahler (1950) quantified this relationship as follows: $S_g = 4S_c^{0.8}$, where S_g is a mean maximum slope angle and S_c is stream channel gradient. this relation (Figure 9) shows that the steeper the hillslope, the steeper are the streams that drain the area. This is the expected relation because the steep slopes provide a large amount of sediment to the channels which, in turn, must be steep to transport it."

The above discussion shows the interrelationship of the slope components of a drainage basin, however, Melton (1958) found relationships between other morphometric components of a basin. As drainage density increases so does the frequency of individual stream segments within the drainage network (Figure 10). In other words, drainage network growth occurs through lengthening of existing streams, but also through bifurcation and addition of a new stream segments to the system.

The mining and reclamation process may effect changes in many or all aspects of drainage basin form. As various elements of a basin, or only a portion of a basin are disturbed by mining it can be expected that related form elements will adjust to the change. For instance, if reclaimed hillslopes are steep relative to receiving stream channels then channel aggradation may occur due to increased amounts of hillslope erosion.

Conversely, if reclaimed hillslope gradients, and therefore erosion are reduced but water yields remain at premining values then stream channels will degrade and excess sediment may be delivered from the basin.

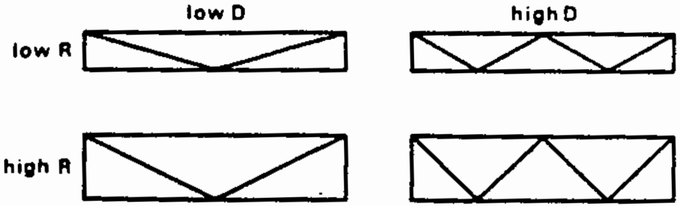

Figure 8.-- Effects of drainage density (D) and relief (R) on hillslope inclination and length (from Chorley, et al., 1984).

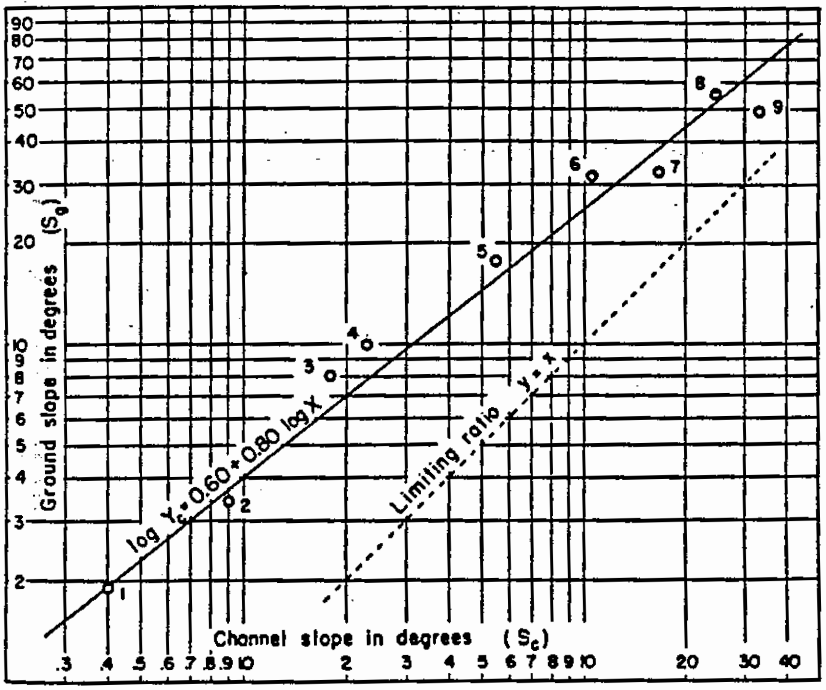

Figure 9.-- Slope ratio, S_c/S_g, for nine maturely dissected regions: 1 and 2, Grant. La.; 3, Rappahannock Academy, Va.; 4, Belmont, Va.; 5, Allen's Creek, Ind.; 6, Hunter-Shandaken, N.Y.; 7, Mt. Gleason, Calif.; 8, Petrified Forest Arizona; 9, Amboy (clay hill), N.J. All data from U.S. Geological Survey, Army Mapping Service or special field maps (from Strahler, 1950)

Controls of Basin Morphology

Relief, lithology, and climate exert a significant influence on the morphology of a drainage basin. Relief is an index of the potential energy of the system available for landscape erosion. Rates of soil and stream bed erosion are directly related to gradient as measured by relief ratio or average basin slope. For instance, Hadley and Schumm (1961) found that annual sediment accumulation from basins in Wyoming is related to relief ration (Figure 11). basin morphology also varies with the geologic material underlying the basin. For instance, erosion resistant rocks with a high permeability will have a low drainage density and erodible impermeable rocks will have a high drainage density.

Lithology has a strong influence on the erodibility and infiltration capacity of the surface materials of a basin. Infiltration capacity determines the percentage of precipitation that will form surface flow available for erosion and sediment transport. Erodibility of the soil surface controls the rate of soil detachment by flowing water. Eccker (1984) found that morphology of basins on the Mesa Verde Sandstone is significantly different from basins on the Browns Park Sandstone and Mancos Shale in northwestern Colorado. The differences are attributed to differences in permeability and erosion resistance of the surface materials. therefore both infiltration capacity and soil erodibility influence processes and morphology of a drainage basin.

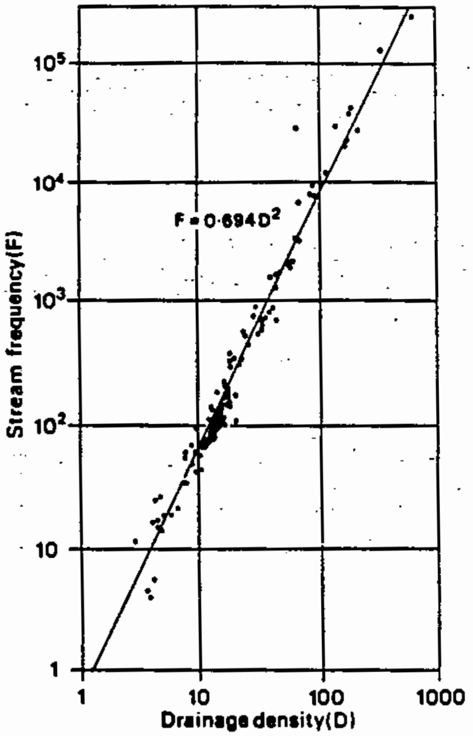

Figure 10.-- Relation between stream frequency and drainage density (miles/miles^2) for 156 basins in the southwestern U.S. (from Chorley, et al., 1984, after Melton, 1958).

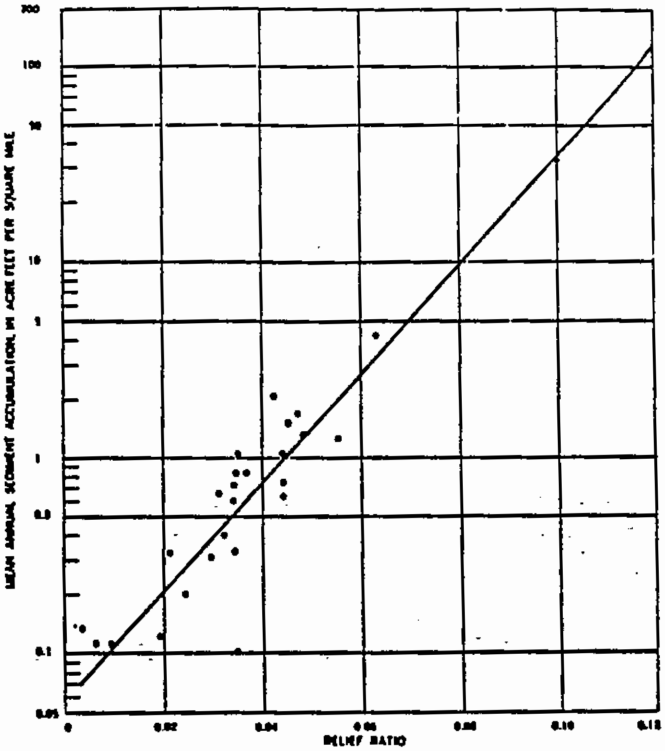

Figure 11.-- Relation between mean annual sediment accumulation and relief ratio for basins on the Fort Union formation (from Hadley and Schumm, 1961).

Structural control of a drainage pattern is significant where geologic formations have been deformed by tectonic processes. Outcrops of resistant bedrock will cause stream channels to turn abruptly at sharp angles or to follow outcrops of erodible materials in a pattern reflecting the planform shape of geologic outcrops. Deformed drainage patterns have been referred to by the shapes of the patterns such as parallel, trellis, rectangular, radial, or annular (Zernitz, 1932). Where drainages form without the influence of geologic controls a tree-like or dendritic pattern forms that is characterized by irregular branching with tributaries joining main streams at many different angles. Mining and reclamation produces a spoil material that is roughly homogeneous in nature, and therefore, a dendritic drainage pattern would be expected to form on a reclaimed surface.

Precipitation input to the drainage basin is controlled by climate. Langbein and Schumm (1958) (Figure 12) shows that sediment yield varies with effective precipitation, with a maximum sediment yield occurring in semiarid climates and lesser amounts for both arid and humid areas. In semiarid regions erosion by fluvial processes is high because there are a sufficient number of precipitation events to cause significant erosion, yet there is poor soil and vegetative cover to protect the surface materials from erosion. In humid areas, erosion by fluvial processes is less than in semiarid regions despite higher amounts of precipitation because of a greater vegetative and soil cover. Drainage basin form in humid regions is also influenced by a greater degree of chemical weathering than in semiarid regions. Arid regions, although lacking almost any protective vegetative cover, do not receive sufficient rainfall to produce high rates of erosion.

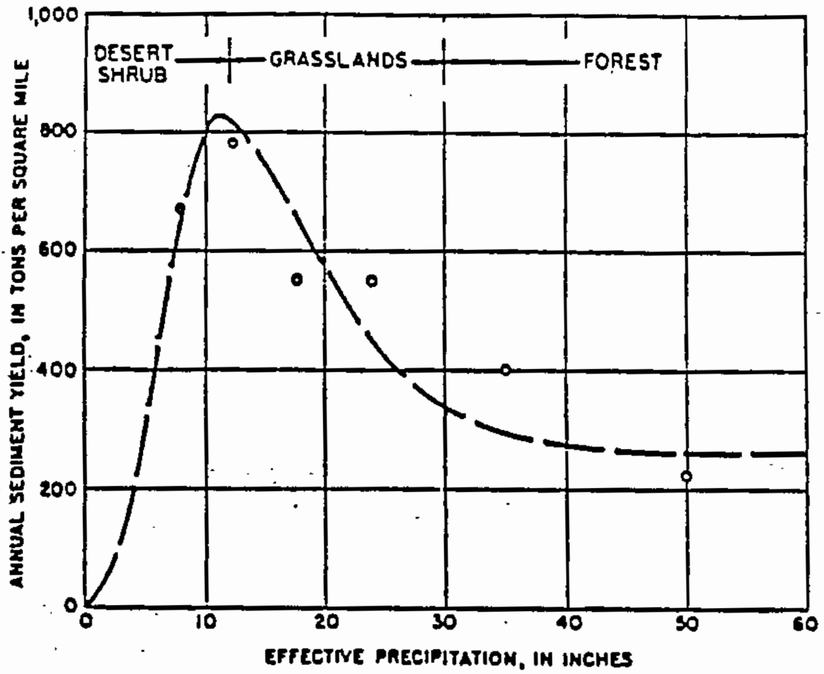

Figure 12.-- Climatic variation of sediment yield as determined from records at sediment stations (Langbein and Schumm, 1958).

Time is an important factor in the evolution of a drainage basin. Glock (1931) proposed an idealized sequence of drainage basin development similar to Davis's (1899) theoretical cycle of erosion. The sequence begins with a single basin of constant initial relief into which a drainage network incises and expands towards the divides. After a period of maximum expansion the network contracts as the interfluves are eroded away and sediment is sorted in the main channel valley. A cycle of basin evolution may take place over thousands or millions of years, a span of time greatly in excess of the mining, reclamation and bond-release period. However, during shorter timespans the character of landscape change varies (Figure 13). Within cyclic time, basin evolution may appear to be progressive with time, however, as erosion of the landscape takes place the existence of threshold conditions may cause abrupt episodes of landscape change that can be described as a dynamic metastable equilibrium. Over shorter periods of time a steady state equilibrium will occur where landscape erosion takes place, sediment will be transported from a drainage basin, but the morphology of the basin does not change. Indeed it should be the intent of reclamation to restore a landscape that functions in a steady state equilibrium with environmental inputs.

Identification of geomorphic thresholds may be extremely important in determining the most stable postmining topography. At certain critical values of drainage basin, hillslope or stream channel morphology erosion rates become excessive and the visual evidence of these rates, such as rills and gullies, will form. Comparison of morphologic features with a measure of energy input to the geomorphic system (i.e., discharge, channel slope, etc.) provides a means of quantifying a threshold for use in topographic design. for instance, Patton and Schumm (1975) plot valley-floor slope versus drainage area (surrogate for discharge) for gullied and ungullied valley floors in northwestern Colorado (Figure 7). Gullied valley floors are presumed to be unstable and for the most part they plot above the line of Figure 14. Similar relationships may be developed for regraded surface mine spoils, such as critical slope-length at which rills tend to develop on hillslopes. Threshold morphologic characteristics can then be used to guide the design of reclaimed topography.

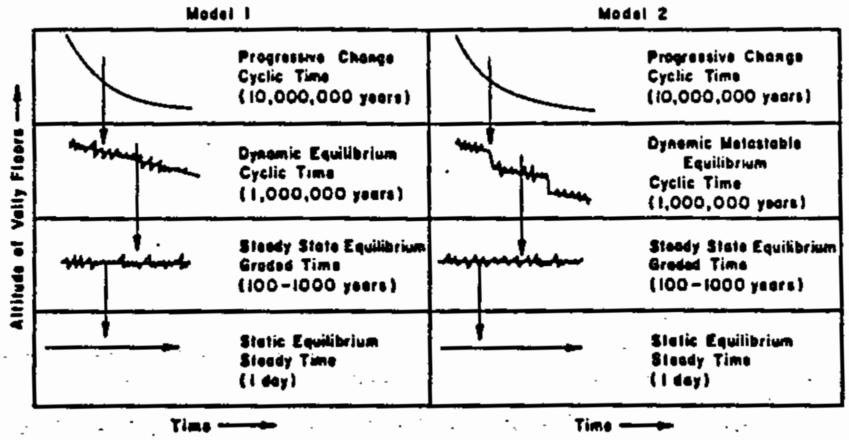

Figure 13.-- Models of landscape evolution: (a) Model 1: equilibrium components of Davis' model of progressive denudation, (b) Model 2: equilibrium components of model based on episodic erosion (from Patton and Schumm, 1975).

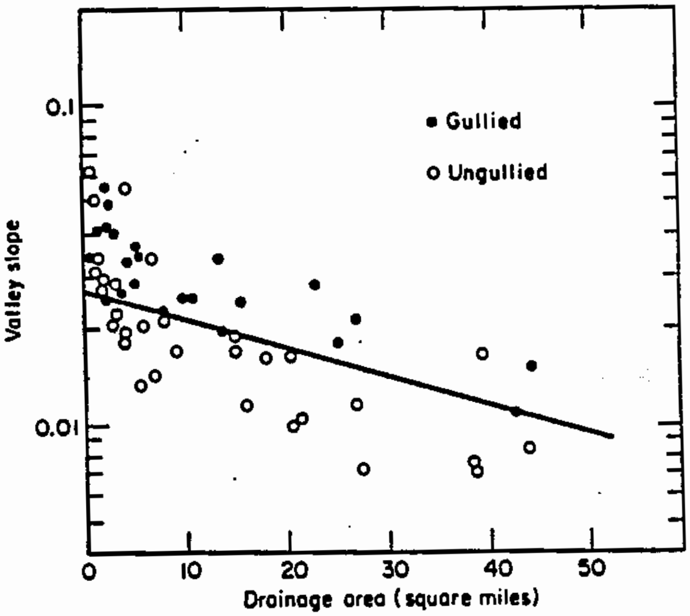

Figure 14.-- Relationship between valley slope and drainage area for gullied and ungullied valleys in the Piceance basin, Colorado (from Patton and Schumm, 1975).

Drainage Basin Design

Reconstruction of all or part of a drainage basin required the integration of hillslope and channel design. Output of sediment and water from a basin is a function not only of the morphology of individual hillslope and channel components but also of the manner in which the components interact. The premining landscape provides one model of stable post-mining topography, however, given the changes brought about by mining and reclamation (i.e., changes in relief, soil erodibility and infiltration) it is likely that other surface configurations will be more stable. Computer models, such as SEDIMOT II (Wilson, et al., date unknown; Warner, et al., date unknown) provide a means of estimating basin sediment output based in part on morphologic characteristics of hillslopes and channels. Sediment output can be minimized by manipulating characteristics of hillslopes, channels, and therefore, the basin as a whole.

Geomorphic relationships are useful in modifying reclaimed topography to compensate for permanent changes in hydrology due to mining and reclamation. For instance, referring back to the plot of Patton and Schumm (1975) (Figure 14) it can be seen that by reducing drainage area for any point on the plot, the point will be moved horizontally to the left, a position of increased stability relative to the threshold line. On a basin scale this can be accomplished by increased stability relative to the threshold line. On a basinscale this can be accomplished by increasing drainage density of stream channels and drainage swales. As shown by Figure 10 this is done by increasing the frequency of streams, that is, adding stream segments that did not exist in the premining topography. By reducing drainage area, and thus discharge, the change that gullies will develop in drainage swales and channels will be greatly reduced.

Manipulating the relationship between hillslope and channel gradients (see Figure 9) may prove to be an important method of sediment control. Low gradient channels have reduced sediment transport capacity, less than normal, sediment will aggrade in these low-gradient channels until slope is increased sufficiently to transport the sediment delivered to the channel. During reclamation there is a period of time before vegetation becomes established when sediment yields may be higher than long-term sediment yields. Designing landscape elements such that aggradation occurs within some areas of a basin may provide a method for controlling initially high rates of erosion.

Manipulating the relationship between hillslope and channel gradients (see Figure 9) may prove to be an important method of sediment control. Low gradient channels have reduced sediment transport capacity. If hillslopes are contributing small amounts of sediment to the channel then incision or gullying of the channel is less likely. Conversely, if hillslope sediment yield is high, then sediment will aggrade in low-gradient channels until slope is increased sufficiently to transport the sediment delivered to the channel. During reclamation there is a period of time before vegetation becomes established when sediment yields may be higher than long-term sediment yields. designing landscape elements such that aggradation occurs within some areas of a basin may provide a method for controlling initially high rates of erosion.

In many areas where surface mining is presently active there is a considerable amount of geologic control on the form of drainage networks. Surface mining removes bedrock controls and replaces it with a fractured spoil material that will no longer exert an influence on either drainage pattern (planview characteristic of drainage network) or hillslope and channel gradient. Hillslope and channel gradients can be reduced to account for the change. In addition, drainage pattern should be modified to a more dendritic form where possible to accomodate the change in geologic materials. Where regional slope is significant drainage pattern will be parallel and basins should be long and narrow (Zernitz, 1932; Eccker, 1984).

Conclusions

Natural landscapes, especially the semiarid western U.S., are dynamic and highly variable systems. Extreme hydrologic events are capable of triggering an instability which will propagate throughout a drainage basin. For instance, in may regions of the West at a given time some channel networks will be incised while similar adjacent drainages are not incised (Schumm, 1977). Regulating the reconstruction of landscapes which are inherently variable and at times subject to rapid change under natural conditions requires the application of performance standards that accomodate the complexity and variability of the fluvial system.

Although quantitative design criteria are lacking (Gregory et al., 1985), a number of qualitative concepts can be incorporated into regrading of surface mine spoil. Hillslopes are more stable at lower gradients and shorter lengths, and complex and concave profiles will produce less sediment. Channel stability can be increased by reducing gradient, drainage area (and therefore, discharge) and maintaining a smooth concave-up profile. breaks in the slope that may occur at the boundary between natural and reclaimed channels can be stabilized by engineering methods. Integration of hillslopes and channels into a drainage network should consider the relationship between channel gradient and hillslope gradient. If possible a slowly aggrading system should be maintained since it is unlikely to upset equilibrium sediment loads.

Sediment control should maintain background levels of sediment concentration to avoid detrimental downstream impacts. Alluvial channels will maintain an equilibrium morphology if the balance between water and sediment flowing in the channel remains within premining limits. An increase in sediment load will induce aggradation of the channel and a reduction or elimination of sediment load may cause degradation and/or bank failure.

Finally, quantitative information on landform response to reclamation is needed to valuable input to future reclamation design. Identification of threshold landforms may provide, for example, maximum values of channel or hillslope gradients above which significant visible erosion of the landscape will occur. Observation of rill and gully development on reclaimed areas coupled with monitoring of water and sediment input and output from this system will be necessary to identify threshold conditions This would require that specified reclaimed areas be exempted from requirements to repair rills and gullies, perhaps as an experimental practice, for a period observation. With proper monitoring and sediment control techniques valuable geomorphic information can be acquired that can be used in reclamation design.

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